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Cerrillos Dam — 3-D Seepage Analysis

by John B. Palmerton
Geotechnical Laboratory

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Waterways Experiment Station
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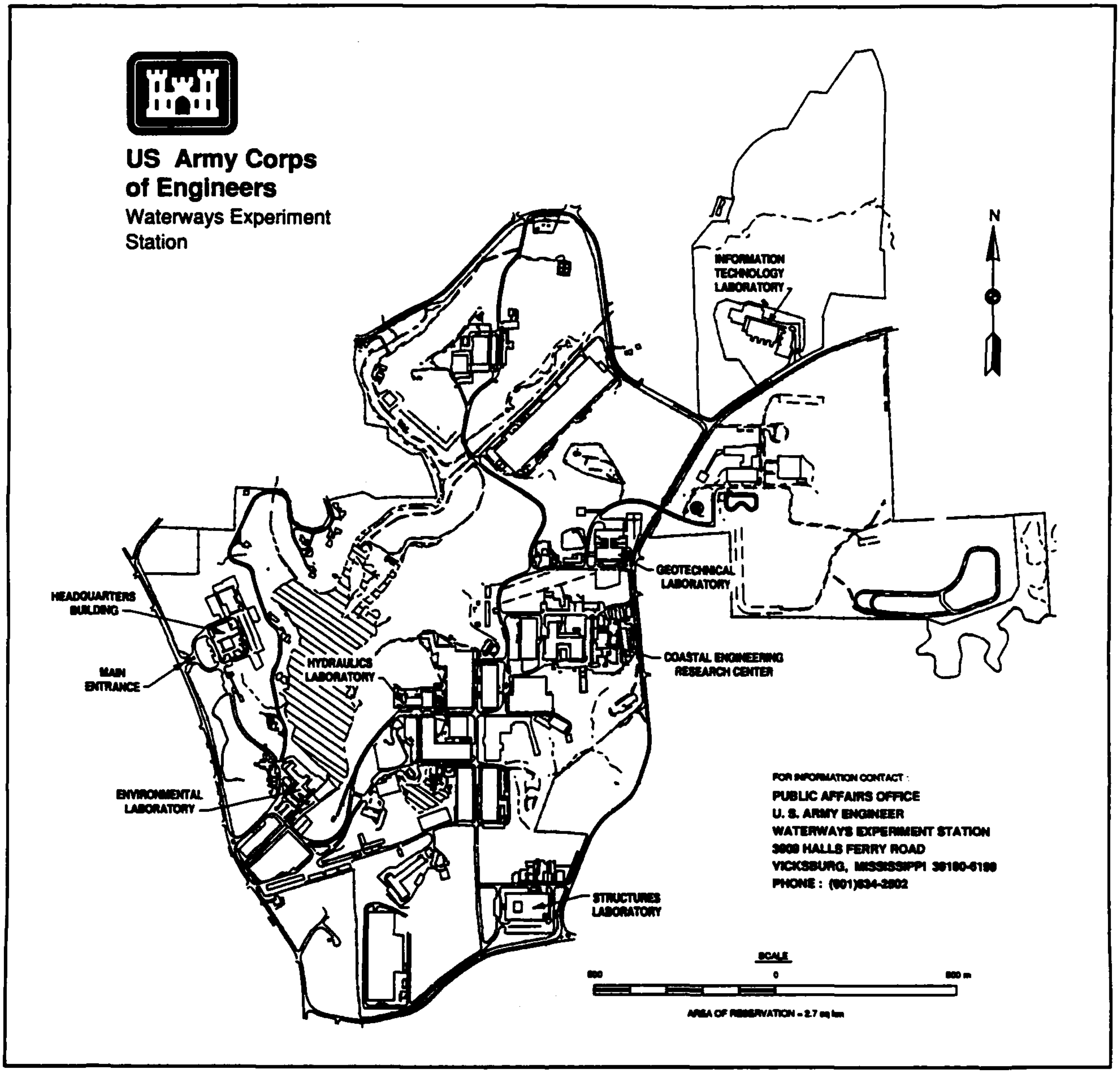

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Preface

This report describes the results of a three-dimensional Finite Element seepage analysis of Cerrillos Dam conducted during the period November 1992 to July 1993. This dam, located near Ponce, Puerto Rico, was recently constructed and the observed foundation seepage was in excess of the design estimate. This study was undertaken as an effort to evaluate the reasonableness of the observed seepage discharge rates. The study was requested and funded by the U.S. Army Engineer District, Jacksonville (CESAJ-EN-G). Technical Monitor was Mr. Paul Shafer, Chief, Geotechnical Branch. Dr. Edward E. Middleton was Chief, Engineering Division, and COL Terrence Salt was Commander of the Jacksonville District.

The study was conducted and the report was prepared by Mr. John B. Palmerton, Rock Mechanics Branch, Soil and Rock Mechanics Division, Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station (CEWES-GS-R). The study was conducted under the direct supervision of Mr. Jerry S. Huie, Chief, Rock Mechanics Branch, and under the general supervision of Dr. Don C. Banks, Chief, Soil and Rock Mechanics Division, and Dr. William F. Marcuson III, Director, Geotechnical Laboratory. Ms Kristine McNamara, Soil Testing Facility (CEWES-GS-GD) prepared the graphical presentation portions of this report.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
cubic feet	0.02831685	cubic meters

1 Introduction

Cerrillos Dam is located near Ponce, Puerto Rico, on the Cerrillos River. The dam is approximately 323 ft high with a crest length of 1,555 ft. Construction of this dam was completed in 1992. Figure 1 is a photo taken in March 1992 which shows the completed structure as seen looking east from the top of the right abutment. The upstream curvature of the dam is readily apparent in the photo as is the inclined outlet structure. The outlet structure is not integral to the embankment, but is founded on the sloping face of a small ridge which extends toward the pool. The left valley wall in the vicinity of the outlet structure was scaled and cleared following a landslide which occurred during the foundation excavation of the outlet structure. The dam consists of a central clay core, a grout curtain extending to a depth of 200 ft, and upstream and downstream rockfill shells with appropriate transition zones. The first filling of the dam occurred in late 1992 and considerable seepage (as intercepted by a toe drain system in the downstream shell) was observed. Analysis of the toe drain observations indicates that approximately 4 cubic ft per second (cfs) was being collected by the drain system at a pool depth of approximately 200 ft (el 495 ft). The planned maximum conservation pool will be 281 ft deep (el 573 ft). The design seepage estimate was 1.0 cfs at the maximum conservation pool.

The U.S. Army Engineer Waterways Experiment Station (WES) was requested by the U.S. Army Corps of Engineer District, Jacksonville, to undertake a three-dimensional (3-D) seepage analysis of Cerrillos Dam in November 1992. This report documents the results of the analyses.

Purpose

The purpose of this study is to conduct a thorough analysis of the seepage regime at the Project site and to provide a tool to evaluate the effectiveness of different concepts for seepage control at the site. It was specifically requested by the District that a 3-D finite element (FE) analysis be conducted.

Background

In November 1992, the author visited the Jacksonville District offices and was briefed by District staff engineers and geologists as to the pertinent details relating to the observed seepage. At the time of this briefing, field evidence indicated that the majority of the observed seepage was coming from the direction of the left abutment. A strong feeling existed among the District staff that the seepage was more than likely due to the presence of a geologic structural unit known as the Ridge (Forming) Limestone. Extensive geologic studies had previously been conducted and their results incorporated in the various Project Design Memoranda, particularly the Feature Design Memorandum No. 17[1] (DM-17) which was issued in 1983. DM-17 presents (among other items) detailed geologic structure maps, the seepage analysis calculations for the designed project (2-D), and results from field tests to determine the permeability of the foundation materials. It was decided during the November meeting to conduct a 3-D FE seepage analysis which specifically included the effects of the Ridge Limestone unit.

[1] In this report, elevations are in feet National Geodetic Vertical Datum (NGVD).

2 General

Pertinent Features at Cerrillos Dam Influencing Seepage

The geologic structure in the vicinity of the dam is characterized by steeply dipping planar and parallel units of limestone, siltstone, and tuff which underlay a very rugged terrain. Surficial soils are either non-existent or are very thin. The bedding strikes N 50-60° E and dips 40-50° SE. Permeability coefficients within these units show a wide variation with the Ridge Limestone exhibiting the highest (by far) permeability (see page 5-3 of DM-17). The Ridge Limestone unit outcrops on the left valley wall in the vicinity of the location of the dam's clay core and the left abutment interface as shown in Figure 2 (taken from Plate 10-22 of DM-17). At the base of the valley, the Ridge Limestone unit is exposed beneath the downstream rockfill shell of the dam as shown in Figure 3 (taken from Plate 10-19 of DM-17). During construction, a grout curtain to reduce seepage was placed by injecting grout in drill-holes to a depth of 200 ft under the full length of the impervious clay core contact with the valley floor and abutments. The pertinent data for estimating the seepage discharge quantities during the design phase are shown in Figure 4. This analysis was accomplished by constructing a flow net (using transformed sections to acount for the variation of permeability with depth). This analysis did not specifically include the Ridge Limestone unit nor did it include the seepage through the abutments above the valley floor. This type of flow net analysis is the typical procedure for Corps of Engineers dams. In most cases the seepage around dam abutments is conservatively (since the pressure head decreases in the abutment zones) accounted for by assuming a crest length which is in excess of the width of the valley floor. However, if the permeability of the materials within the abutments (i.e., the material above the valley floor) differs significantly from those beneath the valley floor, a different type analysis would be indicated. For Cerrillos Dam, the failure to specifically account for the presence of the valley crossing Ridge Limestone unit apparently led to a low estimate for the quantity of seepage. The topography of the region in the vicinity of the dam is shown in Figure 5. The position (outcrop) of the Ridge Limestone unit and the location of the dam, spillway, and intake tower is shown in Figure 6.

The 3-D FE method analyses required some simplifications of the actual geometry. In particular, the valley floor and walls were assumed to be uniform and straight in the vicinity of the dam and the cross-valley curvature of the dam was eliminated. These assumptions are illustrated in Figure 7 which depicts the relationship of the dam, grout curtain, and the Ridge Limestone. Figure 8, in which the rockfill shell is depicted as being transparent, shows the exposure of the Ridge Limestone upstream of the dam and beneath the downstream rockfill shell. This figure also shows the location of the tuff and siltstone units which parallel the Ridge Limestone. The location of the seepage collection system is shown in Figure 9. A cut-away view showing various zones of the dam and foundation is shown in Figure 10. A "birds-eye" view is shown in Figure 11; again, the shells of the dam are depicted as being transparent. A cross section taken parallel to the valley and midway up the left valley wall (looking downstream) is shown in Figure 12. The Ridge Limestone unit is positioned such that water may percolate from the pool into that rock unit along the left valley wall (just upstream of the dam and within the dam's permeable upstream rockfill shell) and be carried in a relatively unimpeded fashion (compared with the surrounding rock) under the grout curtain (which also intercepts a portion of the Ridge Limestone) and then emerges from beneath the downstream rockfill shell and from the lower elevations of the downstream left abutment face. Seepage water which is transported in this manner would be collected by the toe drain system. This mode by which seepage water is transported is also indicated in Figure 13 (in which the geologic materials downstream of the Ridge Limestone are removed from the drawing).

Finite Element Mesh Generation

A very recently developed 3-D FE method seepage computer program which is operational on the Cray Y-MP supercomputer at WES was used for the analyses of Cerrillos Dam. A complete explanation of the theory and application of this computer program is given by Tracy (1991). To use the program, a 3-D mesh (consisting of node points and elements) must be prepared. Each element is assigned a material type which is characterized by a permeability tensor. That is, different Darcy law coefficients of permeability may be prescribed in each of the three coordinate directions. Boundary piezometric heads and boundary flow quantities or flow velocities can be specified as part of the input data. This FE formulation can simulate confined or unconfined flow regimes. For unconfined flow problems (such as Cerrillos Dam) the location of the phreatic surface is established by an iterative process. The output of the program consists of the total seepage discharge quantity, the piezometric head at each node point and the flow velocities. Both the FE method and the graphical flow net technique seek solutions to identical mathematical formulations for seepage flow (i.e., Laplace's equation and Darcy's law); therefore, either method will yield, excluding computational errors, identical results. The FE method may be used to simulate a much larger range of seepage applications since flow net solutions are limited to 2-D applications which must be reduced (by scaling transformations) to equivalent isotropic (uniform permeability in all direction) situations.

To perform the many analyses conducted for Cerrillos Dam during this study, the preparation of a 3-D FE mesh was the first step. Since 3-D FE analysis requires so many nodes and elements to describe even a very simple seepage problem, it was necessary to write a mesh generator computer program (called MESH). The MESH program (a listing is given in Appendix A) was specifically tailored to account for the following pertinent details of Cerrillos Dam:

a. The geologic units, especially the Ridge Limestone unit must strike and dip as discussed in earlier.

b. The elements located in the vertical dam clay core must be identified.

c. The elements located within the grout curtain must be identified.

d. The position of the upstream and downstream dam shells must be identified. Because of their very high permeability, the dam rockfill shells were not included in the FE mesh. However, the position of the shells were needed to simulate the effect of corrective treatment (i.e. shotcreting).

e. Depending on the height of pool being considered, the node points for which boundary piezometric heads are to be applied must be identified.

The complete details of the automatic mesh generator are too lengthy for inclusion herein. In brief, a box-like (see Figure 14a) mesh with a pair of each element's faces slanting parallel to the strike and dip of the geologic units (specified to be striking at N 55° E and dipping 50.7° SE) was first generated. The height of the box-like grid is dependent upon the specified pool height. The North axis was taken to be in the positive y direction, the East axis is in the positive x direction, and z is positive upward. The above values for the strike and dip leads to an apparent dip of 35° E with the x-z (or cross valley) plane (which is also the same angle that the valley walls make with the horizontal plane), and an apparent dip of 45° S with the y-z plane (or longitudinal plane). Following the generation of the box-like mesh, the valley is created by locating the elements whose centers lie above the valley floor and between the two valley walls (see Figure 14b). All of those elements, excepting those within the dam's clay core, are then removed. The nodes and elements are renumbered so that only those nodes and elements which are still present (i.e., not removed) shall be used in the FE analysis. Those elements which lie between the planes delineating the grout curtain and the dam core are then associated with the material type for those zones. Finally, depending on the specified (for a particular problem) height of pool, the nodes which lie on the valley floor and valley walls upstream of the dam and on the upstream face of the clay core are identified for specification of the boundary piezometric head (e.g., 200 ft). In a similar fashion, the boundary piezometric head on the nodes on the downstream valley and downstream face of the clay core are set to the tailwater head (zero).

The overall dimensions of the box-like mesh is 3,141.6 ft in the x, or cross valley dimension, 2,000 ft in the y, or longitudinal direction, and a maximum height, z of 1,200 ft as shown in Figure 15. (For each case for which an FE analysis was made, the height of the box was set at the variable elevation of the pool). The width of the valley floor (which is assumed to be a horizontal plane) is 428 ft. The valley walls rise to a maximum height of 350 ft at an angle of 35° to the horizontal. For the case of a 350-ft pool height, the number of (final) generated elements is 8,283, with 10,810 nodes; for a 100-ft high pool, 7,340 elements and 9,405 nodes are generated.

Material Properties and Model Calibration

As previously stated in paragraph 5, a good amount of field permeability testing was conducted in years past for the Cerrillos Dam project. These field tests led to selection of the permeability coefficients listed in Figure 4. The k (Darcy permeability coefficients) values ranged from 1.4×10^{-3} cm/sec near the ground surface to 1.4×10^{-4} cm/sec at depths below the surface greater than 200 ft. Water pressure injection tests conducted at the site indicated permeability values ranging from 5.1×10^{-3} cm/sec in the Ridge Limestone to 2.5×10^{-5} cm/sec at greater depths. A decrease in permeability with depth is almost always observed at most sites. This decrease is due to overburden caused stresses causing cracks and rock joints to be more tightly closed at depth. The 2-D case (with the k values as listed) shown in Figure 4 was simulated with the 3-D FE program by setting the permeability coefficients beyond the base width of the valley floor to a very low value (1×10^{-12} cm/sec) and then multiplying the computed seepage discharge by the ratio of the length of the hand-calculated section (1,555 ft) to the width of the valley floor in the 3-D model (428 ft). As desired, a result very near to the seepage discharge of 1 cfs noted in Figure 4 was computed by the FE program. Further 2-D simulations were made to determine which uniform rock permeability value would also yield a seepage discharge of 1 cfs. A k of 1.22×10^{-4} cm/sec assigned to all rock below the valley floor yielded 1 cfs. Because of the steeply dipping beds and the often apparent decrease in permeability with depth, no attempt was made to consider anisotropic permeability properties. A rational method for assigning principle permeability tensor directions is too difficult.

3-D Finite Element Computations

Even though the 3-D FE program (employed for 2-D simulations) yielded a close comparison to the hand calculation, the issue of what k values to assign to the rock above the valley floor was not yet resolved. Various trial computer simulations for which various combinations of k values for the Ridge Limestone, the surrounding rock formation, and the permeability of the grout curtain were conducted. After an examination and discussion of these simulations with District engineers and geologists, the set of permeability coefficients listed in Table 1 was selected. The delineation of the zones is shown in Figure 15.

The combination of permeability coefficients listed in Table 1 yielded an excellent estimate for the observed seepage discharges at the project for a pool height of about 200 ft. The predicted seepage discharge versus pool elevation is shown in Figure 16 (lower curve). If the pool elevation is permitted to continue its rise (without further remedial efforts to control the seepage), a seepage discharge of approximately 6.5 cfs (at the maximum conservation pool) is predicted. Data which are gathered as the pool rises in the future may also be used to modify the material properties in order to refine the predictions. Table 1 indicates that the rock below el 105 (400 ft below the valley floor) was considered to be impermeable. The upper curve in Figure 16 shows the effect of assigning a k value of 1×10^{-4} cm/sec to the rock below el 105 ft. Only a small increase in seepage discharge is predicted. Impermeable lower rock zones were desirable to maintain compatibility with the 2-D flow net calculations. Typically, each iterative 3-D FE analysis required a total of 2 to 3 min of processor time (and 10 to 15 min of wall clock time) for completion on the supercomputer. The MESH grid generator program required approximately 12 sec of supercomputer processor time to generate about 8,000 elements and 11,000 nodes.

Table 1

Grout curtain (200-ft depth below clay core)	1.0×10^{-6} cm/sec
Impermeable clay core of dam	6.4×10^{-7} cm/sec
Ridge Limestone unit	5.0×10^{-3} cm/sec
All other foundation rock units above el -105 ft[1]	1.0×10^{-4} cm/sec
All foundation rock units below el -105 ft	Impermeable

[1] El 105 is 400 ft below the valley floor which is at el 295.

The 3-D FE analyses were not conducted for the purpose of predicting seepage discharges at this specific site. Prediction is not the issue since the answer is already known. Further, since the seepage discharges are generally linear with respect to pool height, the simple extrapolation of field observations would provide as good (or better) a predictive capability as the computer model. Instead, *the usefulness of this study has been the demonstration that the observed higher than estimated seepage discharges at Cerrillos Dam have been replicated in a rational manner that did not require any major modification of the understanding of the rock permeability properties which existed during the design phase.* It is doubtful that 2-D (whether FE of flow net) analysis could have rationally predicted the higher seepage discharges. The complicated geologic conditions necessitate a 3-D analysis. Had a 3-D FE seepage analysis of Cerrillos Dam been attempted during the design phases of the project, it is questionable if the now-measured seepage discharges would have been exactly predicted. However, since the Ridge Limestone had been identified as a very permeable geologic unit, any reasonable 3-D analysis in which different permeability combinations were varied would certainly have served to alert the designers of a potential problem. The foundation permeability model presented in Table 1 presumes that the Ridge Limestone is 50 times more permeable that the other foundation rock. Field permeability tests bear out the reasonableness of the modeled permeability coefficient values.

A useful and important application of 3-D FE modeling is the evaluation of the effectiveness of engineered modifications for seepage control. For example, it has been suggested that the placement of a layer of (impermeable) shotcrete on the upstream valley wall exposures of the Ridge Limestone might be effective in lowering the seepage discharges. However, during the construction of the dam, the upstream rockfill shell was placed against the exposed Ridge Limestone on the left abutment. Therefore, it will not be possible to shotcrete the Ridge Limestone buried beneath the upstream shell without the shell's removal. It was fairly simple to modify the MESH program so that the layer of elements within the Ridge Limestone adjacent to the pool could be made more impermeable (i.e. changed to $k=6.4 \times 10^{-7}$ cm/sec). The simulations of shotcreting the Ridge Limestone (a) only above the upstream shell, (b) only below the upstream shell, and (c) the simulation of shotcreting the entire left valley wall upstream exposure were undertaken. Figure 17 shows the result of these simulations. The upper curve shows the predicted seepage discharge for no placement of shotcrete (this is also the lower curve shown in Figure 16). The next lower curve shows the seepage discharge prediction for placement of shotcrete only on the now visible (and accessible) upstream Ridge Limestone face above the upstream shell. The third lower curve shows the seepage discharge for placement of shotcrete (or perhaps grout) only on the exposure of Ridge Limestone now buried by the upstream rockfill shell. The fourth lower curve is for shotcrete placement on all of the upstream exposed valley wall limestone. It is apparent from these curves that partial shotcreting will not be nearly as effective as complete coverage of the highly permeable Ridge Limestone unit. As the pool is raised, the portions of the untreated limestone beneath the shell will still cause considerable leakage because the water pressure head along those untreated faces will continue to rise. The lower curve in Figure 17 is indicative of the best that could be expected with any treatment of the Ridge Limestone. This curve was obtained by presuming that the permeability of the Ridge Limestone is the same as the surrounding rock (i.e. $k=1 \times 10^{-4}$ cm/sec). Also notice that the predicted seepage discharge for this "best case" scenario is approximately 1.0 cfs (the 2-D flow net "design" estimate) at the maximum conservation pool elevation.

The effect of deepening the grout curtain to lessen the amount of seepage discharge is shown in Figure 18. It is seen from this plot that an increase in depth of 100 ft (to a total depth of 300 ft) would reduce the seepage quantity to 5.3 cfs (from the estimated seepage quantity of 6.5 cfs at the conservation pool elevation), an 18 percent improvement. Doubling the depth of the grout curtain to 400 ft would reduce the seepage quantity to 4.5 cfs, a 31 percent improvement. The flattening of the curve at larger grout curtain depths is not favorable to this method of seepage reduction.

The 3-D FE program produces much more output information than simply the total seepage discharge. Other types of output include the piezometric head at each node point, the position of the phreatic surface, and the flow velocities within each element. For example, a 3-D plot of the piezometric heads is shown in Figure 19. A cross section along the valley center shown in Figure 20 illustrates the high head gradient across the dam core and grout curtain. Flow velocity plots are shown in Figures 21, 22 and 23. These plots indicate the absolute magnitude of the velocity without regard to direction of flow. Figure 21 shows that the region of higher flow velocities are concentrated in the zones which comprise the Ridge Limestone. Figure 22 shows the concentration of seepage velocity along a vertical cross section just downstream of the dam core; again, the higher velocities are concentrated within the Ridge Limestone. The seepage velocities along a horizontal section taken immediately above the base of the dam are shown in Figure 23. Because of the large number of nodes and elements required for practical problems, it was necessary to write additional computer programs to process the output data file generated by the 3-D FE program. Four computer programs, named HEADS, PREFLOW, FLOWS, and FLOVEC (see Appendix A) were written during the course of this study to process the FE output data files. These programs were written in FORTRAN for a personal computer. The FE output file(s) (about 3 Mbytes in size) were retrieved from the supercomputer over the WES fiber optic network and stored on the personal computer. The HEADS program examined the FE output file(s) and sorted and stored the data into smaller sub-files. Each sub-file contained the piezometric head values on numerous planar sections passing through the FE mesh. These sub-files were then processed by a contouring program named McCON (Palmerton 1992). A similar function was performed by the PREFLOW and FLOWS programs for the output of seepage velocities at the element centers. The FLOVEC program prepared graphical plots of the flow velocity direction vectors.

Examples of the contour plots are shown in Figures 24 through 26. The contours of piezometric head on a horizontal plane at el 45 ft (250 ft below the base of the dam) caused by a pool depth of 200 ft (el 495 ft) are shown in Figure 24. The contour values are in terms of elevation. Notice the high head gradient near the center of the plot where the water flow is restricted by the grout curtain. Also notice that the heads are somewhat higher (on the order of 15-20 ft) toward the left abutment (right side of plot). The higher heads are due to the presence of the more permeable Ridge Limestone in the left valley wall. The piezometric head contours at el 245 (50 ft below the base of the dam) are shown in Figure 25. Piezometric head contours along a vertical longitudinal plane located at x = 1,713 ft (see Figure 6 for orientation) are shown in Figure 26. The piezometric heads decrease quite rapidly across the clay core and grout curtain.

Vector plots of the computed direction of flow along various sections are shown in Figures 27 through 35. Plots of this type are valuable aids in visualizing the character of the seepage paths. Figures 27, 28, and 29 show the direction of the flow on horizontal planes situated at el 70 (225 ft below the base of the dam and 25 ft below the grout curtain), el 270 (25 ft below the base of the dam), and el 370 (75 ft above the base of the dam). The vectors from the larger circles denote the direction of the flow in the Ridge Limestone. As the elevation of the sections increase, the position of the Ridge Limestone (due to the dip angle of the unit) apparently migrates toward the upper left on the plots. The small circles and large solid circles indicate that the component of the velocity is toward the eye; the "x's" indicate the opposite. All of these figures give the result for a specified pool height of 200 ft (and a total seepage discharge of 4.3 cfs – the case for no shotcrete placement). The data points, which appear to be missing in Figure 29, are the result of the 3-D FE program collapsing the mesh so that no points lie above the phreatic surface. The phreatic surface is also somewhat higher in elevation on the left side of the valley (right side of plot) as will be discussed below.

Vector flow plots on vertical longitudinal sections located at x=1,606, 2,034, and 2,320 ft (see Figure 6 for orientation) are shown in Figures 30, 31, and 32. These sections are taken near the center of the valley floor, mid-way up the left valley wall at approximately the pool elevation, and parallel to the left ridge some 35 ft beyond the crest. Again, the large circles indicate the location of the Ridge Limestone on each of the sections. The 200-ft pool height is indicated on the plots. It is interesting to note that Figure 30 shows the direction of flow within the Ridge Limestone to be upstream as it emerges upward from the valley floor. Again, the small circles and the large solid circles indicate that the (cross valley) component of the flow is toward the eye, and the "x's" indicate that the flow is opposite, or away from the eye.

Vector flow plots on vertical cross valley sections are shown in Figures 33, 34, and 35. The section shown in Figure 33 is taken approximately 250 ft downstream of the axis of the dam, Figure 34 is taken parallel and through the axis of the dam and Figure 35 is taken 250 ft upstream. Downstream of the dam (Figure 33), the flows are directed toward the valley; upstream (Figure 34), the flows are generally directed away from the valley with some exceptions in the Ridge Limestone (large circles). For the section along the dam axis (Figure 35), the flows are still directed outward from the valley on the right valley side (left side of the plot), but tending to flow toward the valley on the left valley wall. These plots all indicate the pool elevation and the location of the grout curtain.

The 3-D FE computer program computes the location of the phreatic surface and adjusts the mesh so that the portions lying above this surface collapse to the surface. For an unconfined seepage analysis, the phreatic surface is defined to be that surface on which the elevation head is equal to the piezometric head. The output data from the 3-D FE analysis (for a pool height of 200 ft) were examined by a program entitled PHREAT (see Appendix A) written during this study and the points (and their coordinate location) which were identified as being on the phreatic surface were extracted. These data points were then processed by the McCON contouring program and contours of the phreatic surface were plotted as shown in Figure 36. The McCON contouring program may also be used to prepare profiles on multiple sections perpendicular to the plane of the contour plots. Figure 37 shows the profiles of two sections taken downstream of the dam axis and two sections taken upstream (see Figure 21 to locate the section numbers). Notice in Figure 37 that the presence of the Ridge Limestone unit causes the phreatic surface to be higher on left side (right side of the plot) of the valley than on the right side by 10 to 15 ft as was also noted earlier.

3 Conclusions and Recommendations

The 3-D FE analyses provided a rational method for gaining a good understanding of the seepage flow characteristics in the abutments and foundation of Cerrillos Dam. The complicated geologic conditions in the vicinity of the Dam require a 3-D modeling capability. The supercomputer can quickly process data sets of up to 10,000 nodes and elements (100,000 nodes and elements could be analyzed) and the fiber optic network permits a rapid means for transmitting data back to a personal computer for other specialized treatment. The adaptation of the 3-D FE program for other dams or situations will require the writing of a grid generator program (similar to the MESH program). It is much too laborious and error-prone to attempt to supply the location of the nodes and elements by a manual process.

The use of 3-D FE analyses to evaluate the effectiveness of proposed corrective actions (such as shotcreting or grouting the permeable units) is an effective engineering approach. Two-dimensional analysis can not address many issues of this type.

Because of the availability of 3-D FE computer programs, it is recommended that analyses of these types be conducted for all projects which present the possibility of a 3-D effect on design computations. Even for cases involving seepage that may adequately be formulated in 2-D form, the use of numerical models (2-D FE models) should receive serious consideration for use. These numerical models generally do not place restrictions on the manner in which different permeability zones are conceptually assimilated. Conceptual restrictions generally do apply for manually constructing flow nets, especially if the transformed section must be considered. That is to say that flow net construction techniques may require unnecessary oversimplification of the conceptual permeability model. For situations where multiple zones and anisotropic permeability must be included, a numerical model is, for all practical purposes, mandated.

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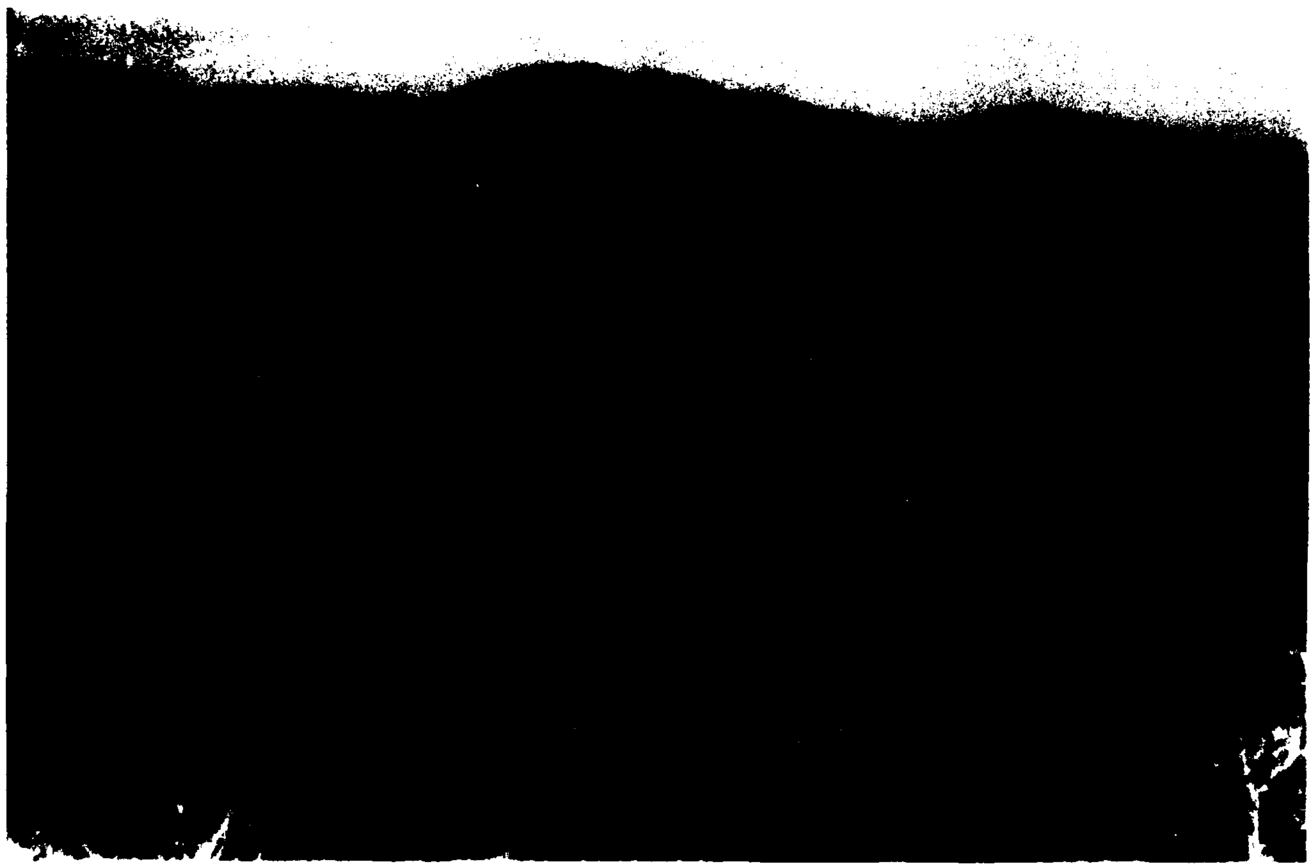

Figure 1. View of Cerrillos Dam

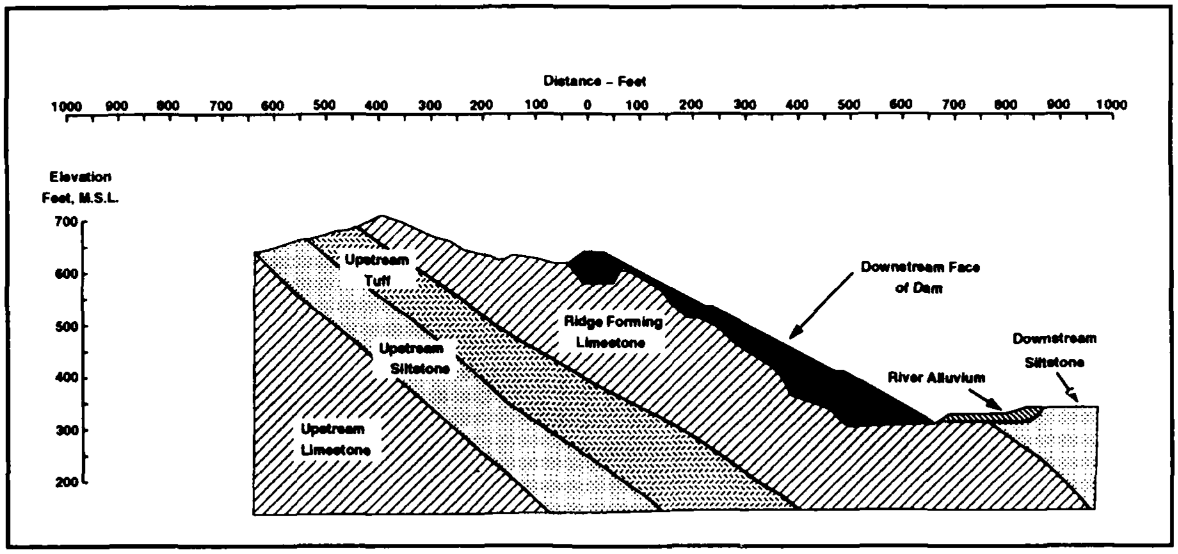

Figure 2. Selected dam cross section near top of left abutment

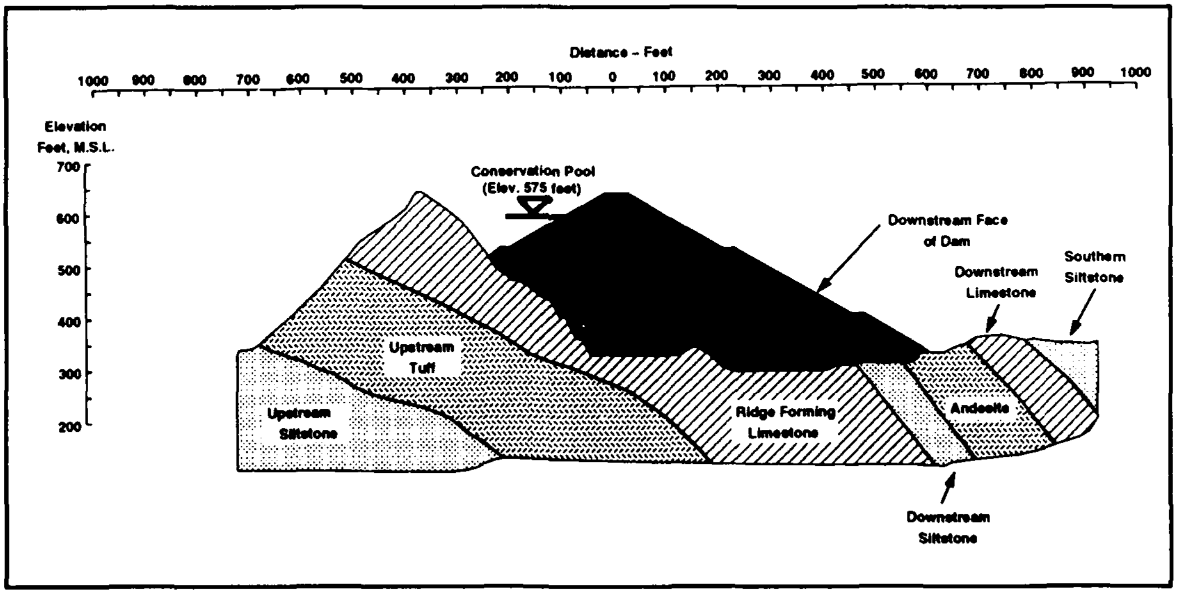

Figure 3. Selected dam cross section near base of left abutment

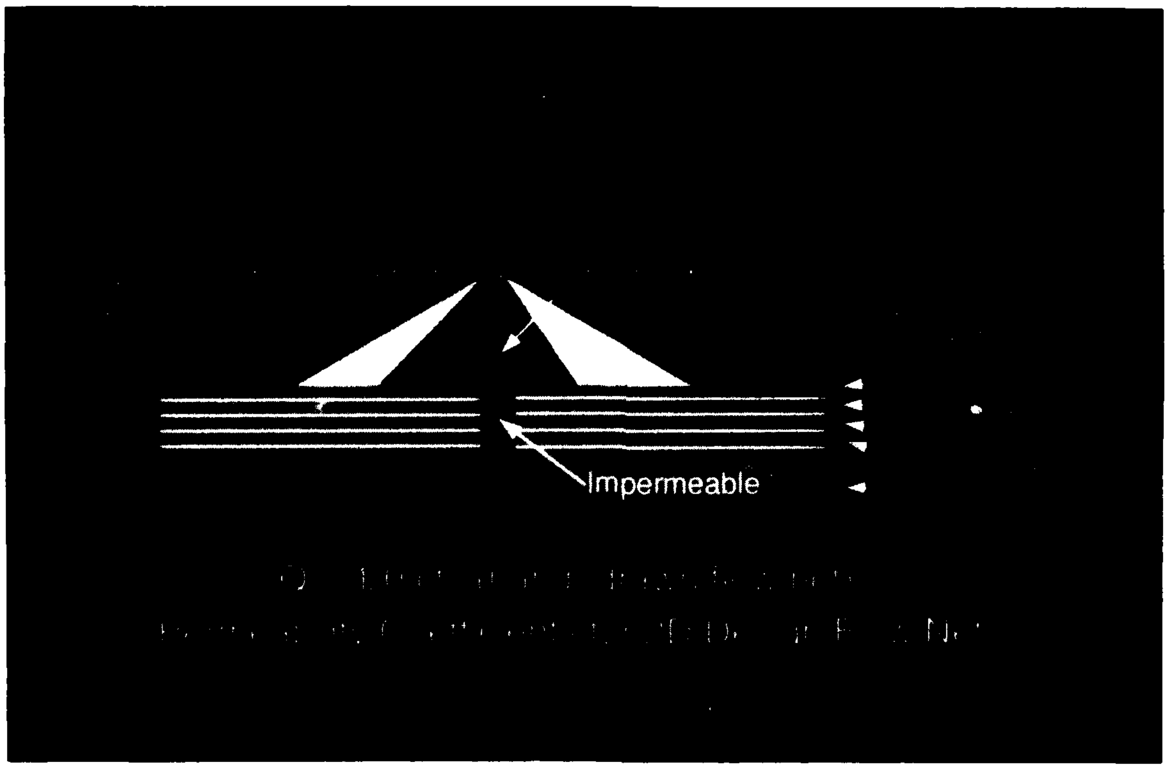

Figure 4. Dam cross section and permeability coefficients for 2-D flow net analysis

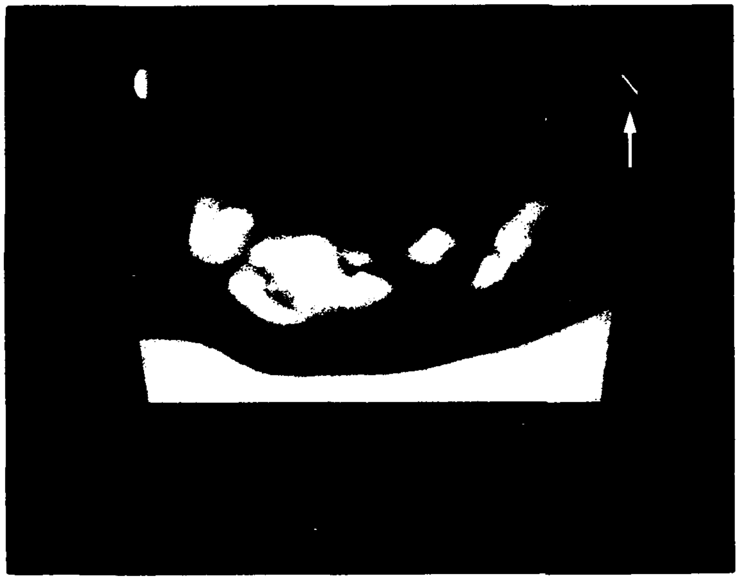

Figure 5. Digitized terrain near Cerrillos Dam. (View to north)

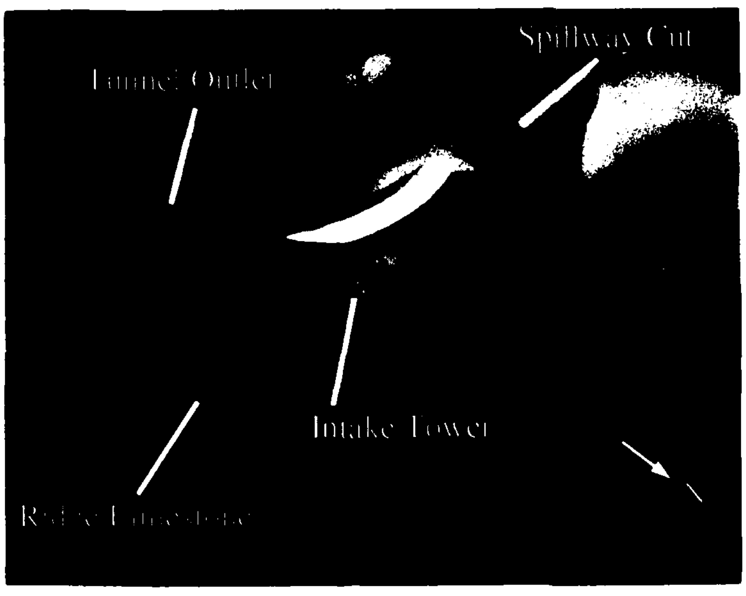

Figure 6. Topography with dam and location of Ridge Limestone

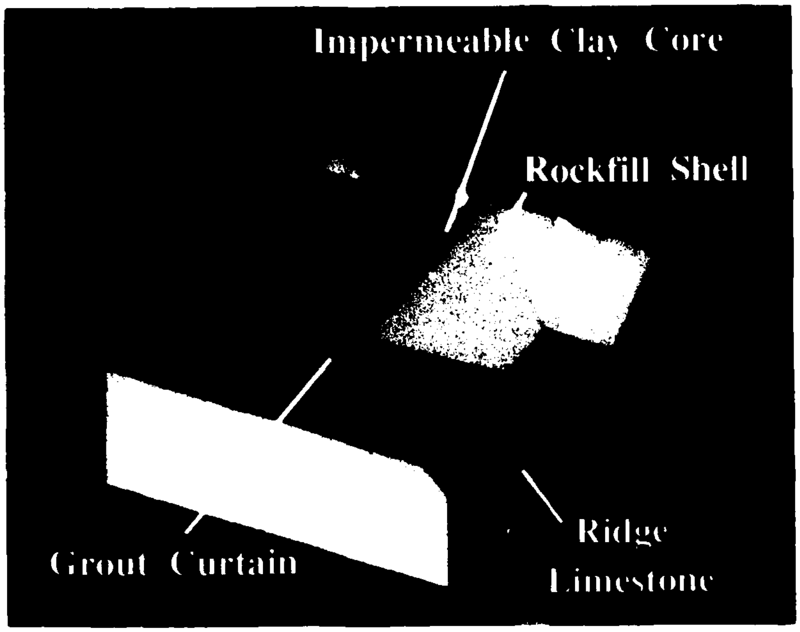

Figure 7. Simplified 3-D model dam, grout curtain and Ridge Limestone

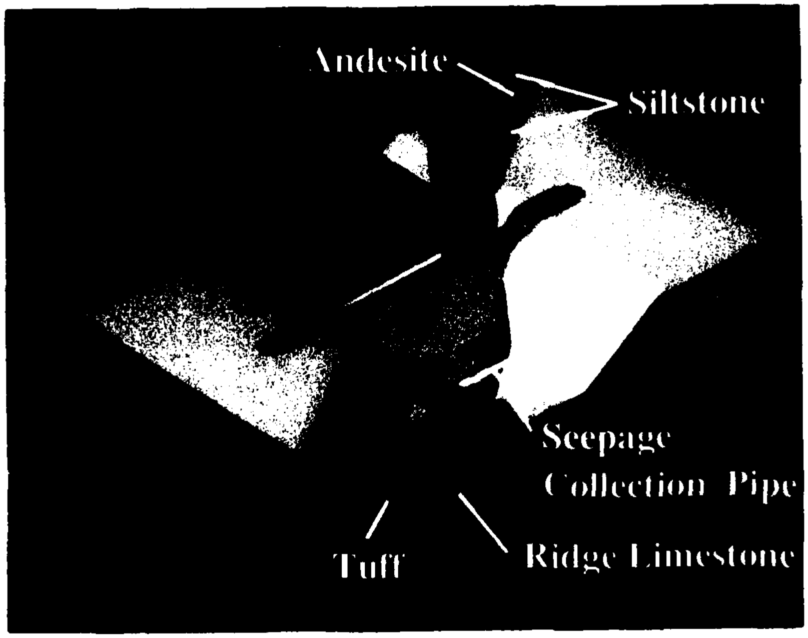

Figure 8. View showing geology. (Rockfill shells shown as being transparent)

Figure 9. Close-up view showing seepage collection pipe

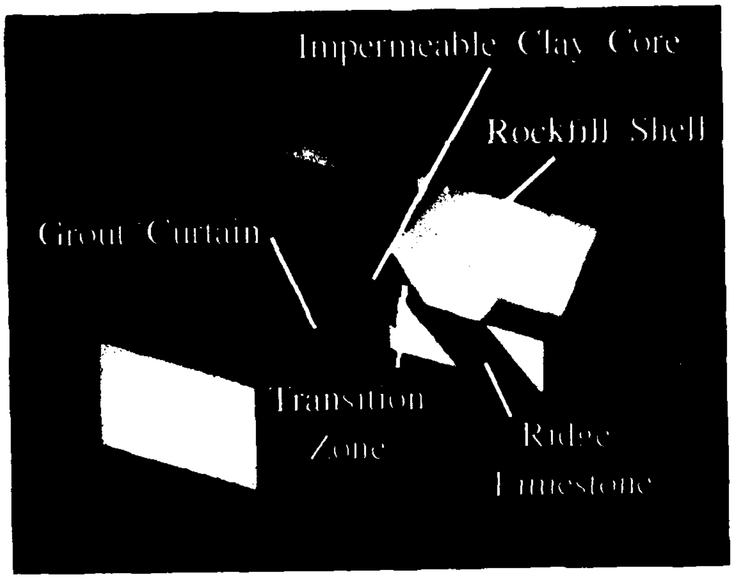

Figure 10. Cut-away view of dam

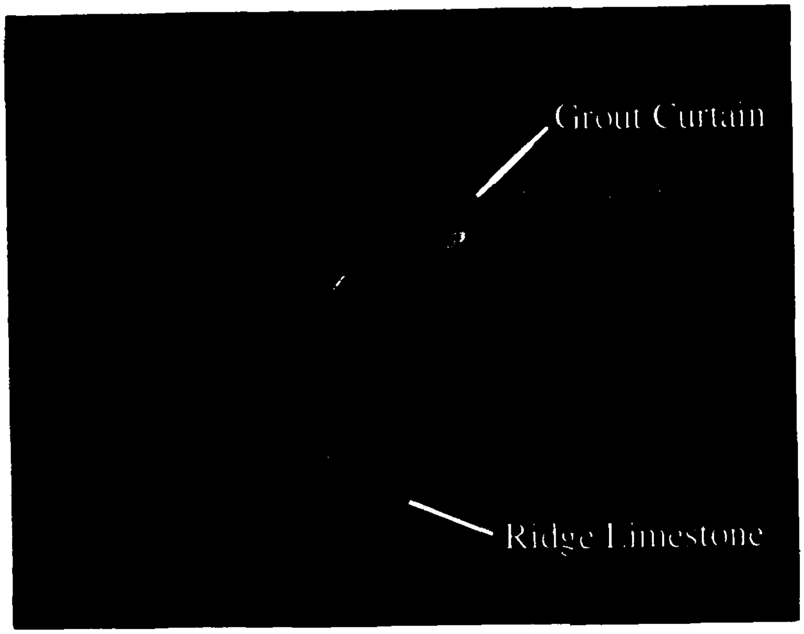

Figure 11. Overhead view of dam

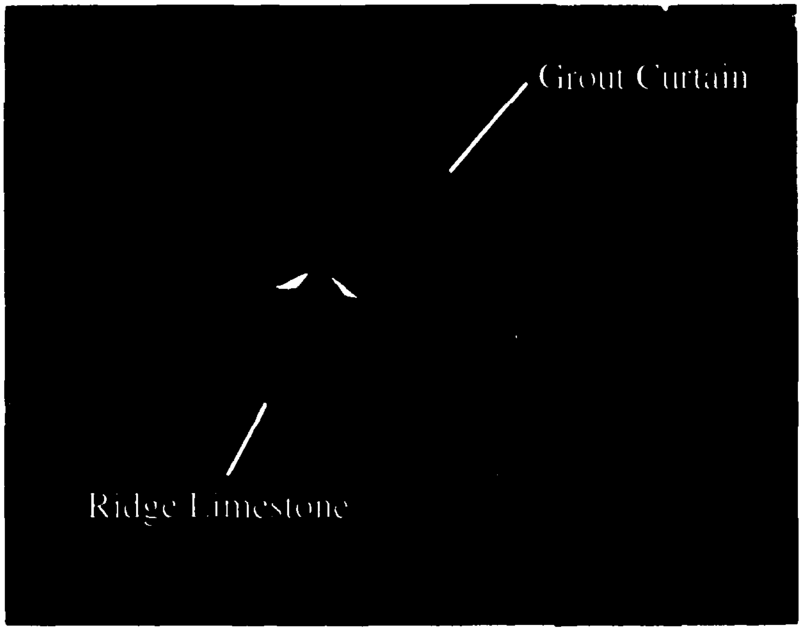

Figure 12. Section through dam and grout curtain midway up left valley wall

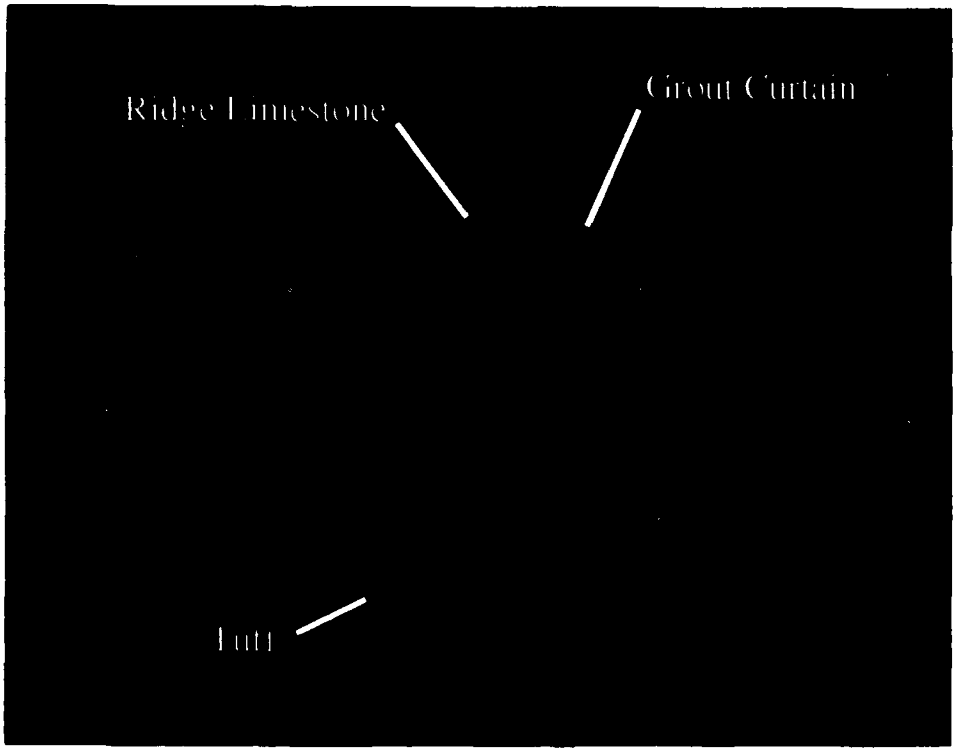

Figure 13. Illustration to indicated seepage path below grout curtain

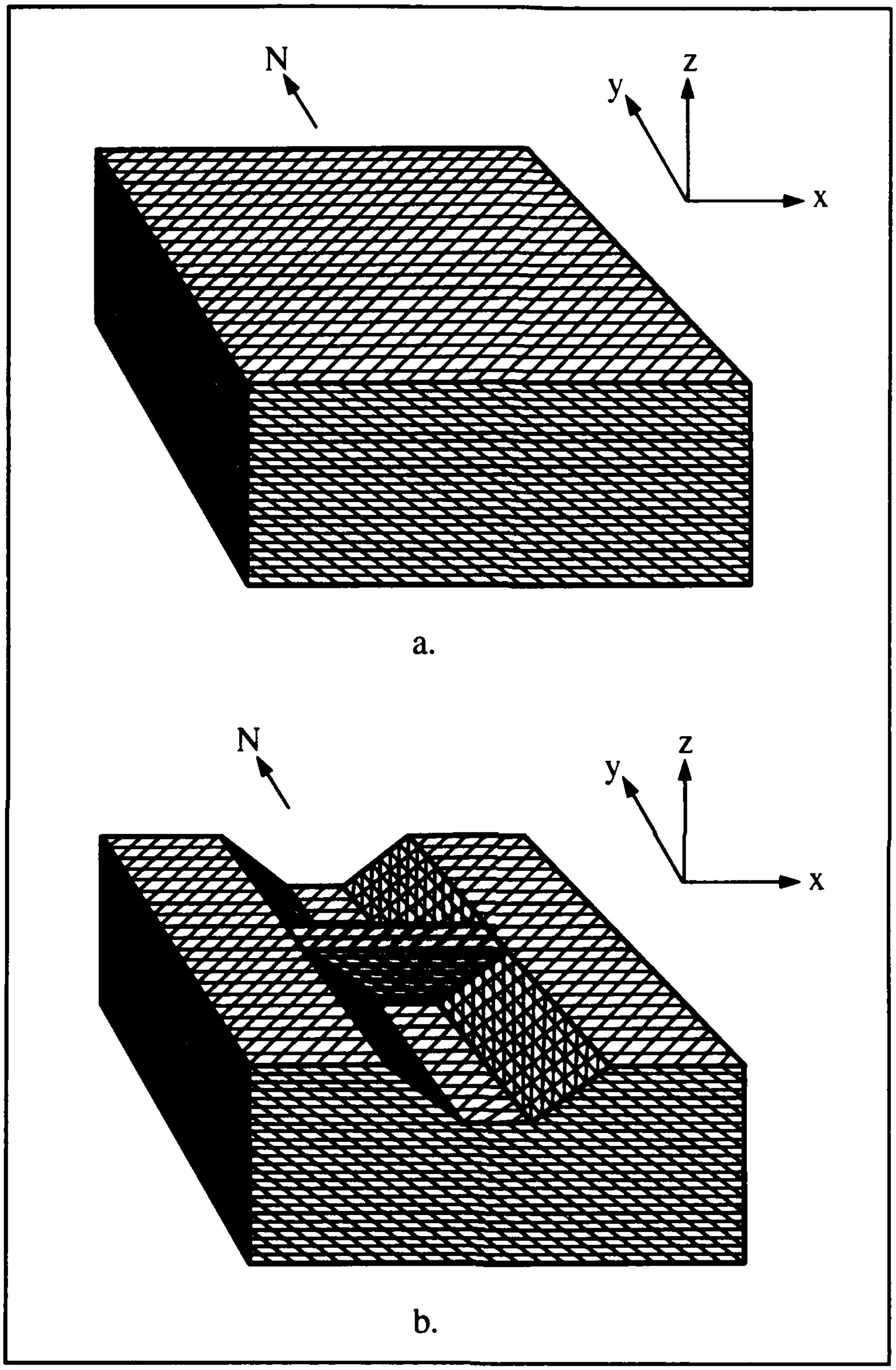

Figure 14. 3-D finite element mesh

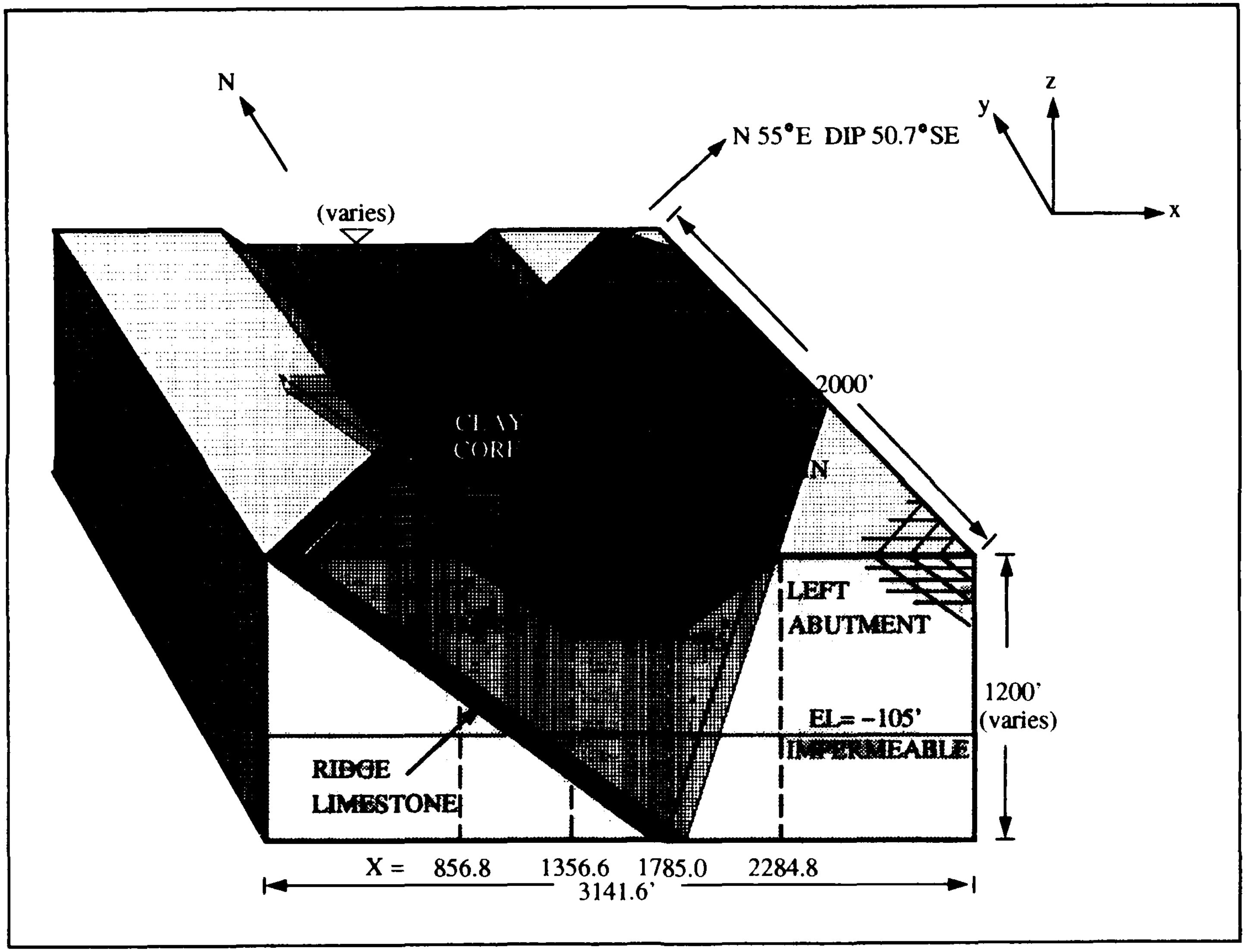

Figure 15. Pertinent dimensions and features of 3-D FE mesh

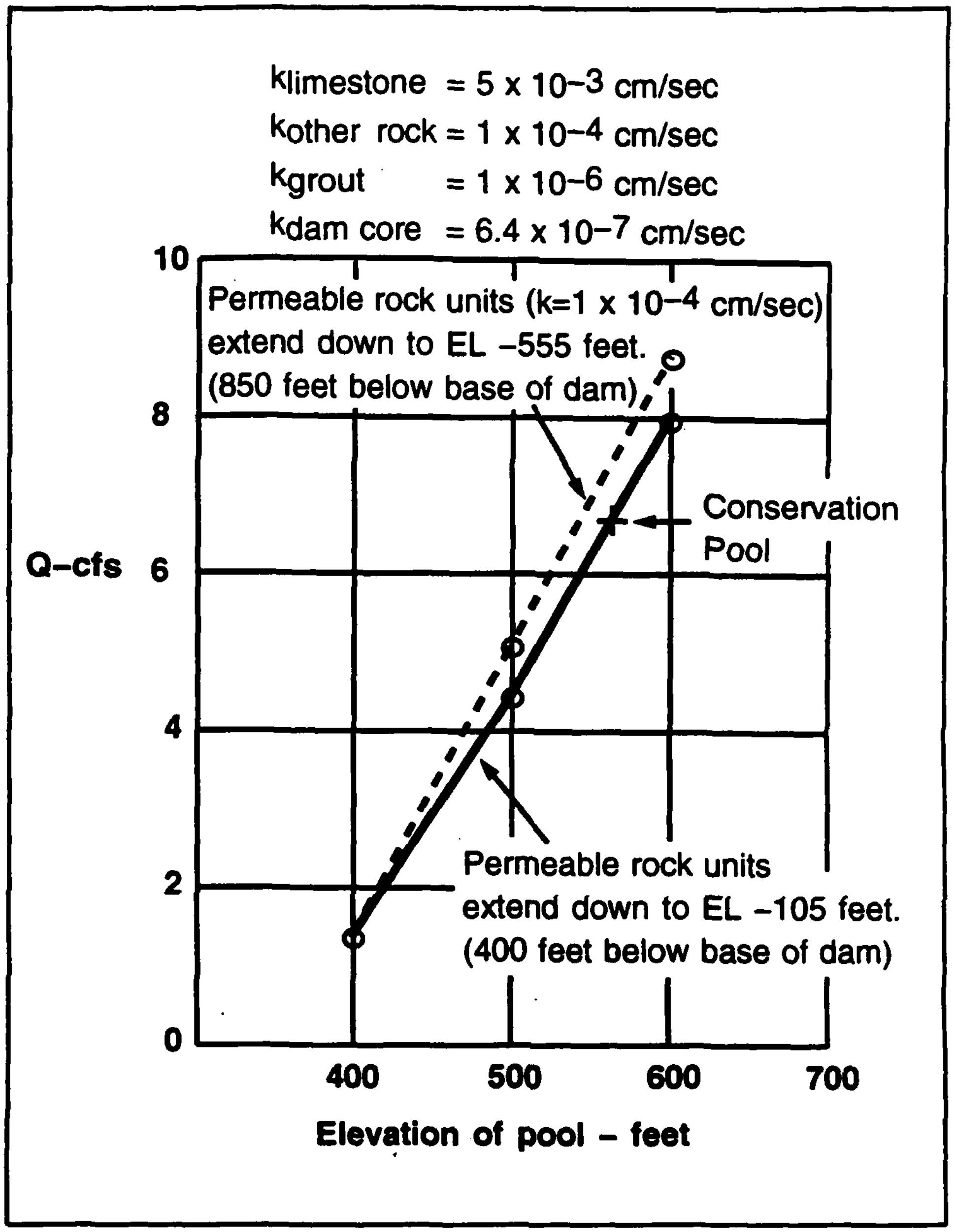

Figure 16. Predicted seepage discharges from 3-D FE analysis

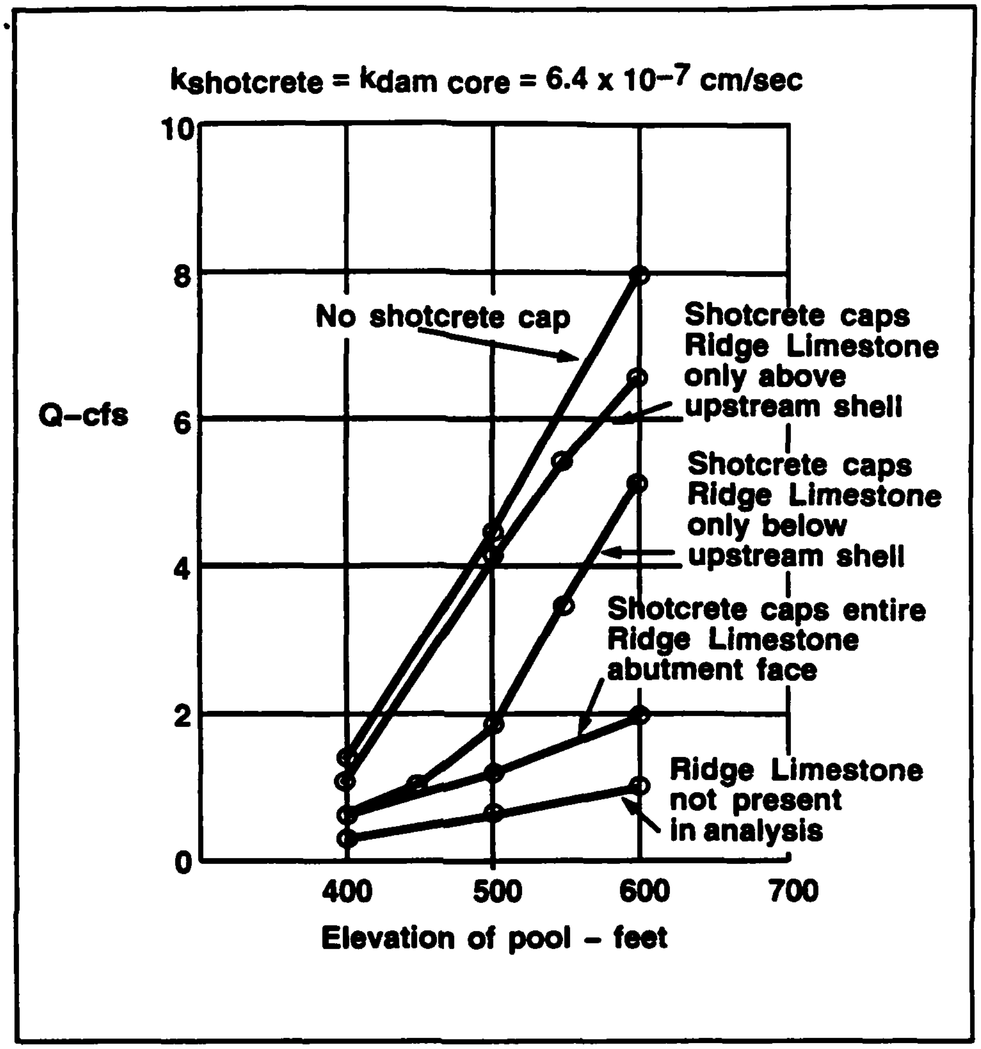

Figure 17. Effect of placement of shotcrete on left valley wall

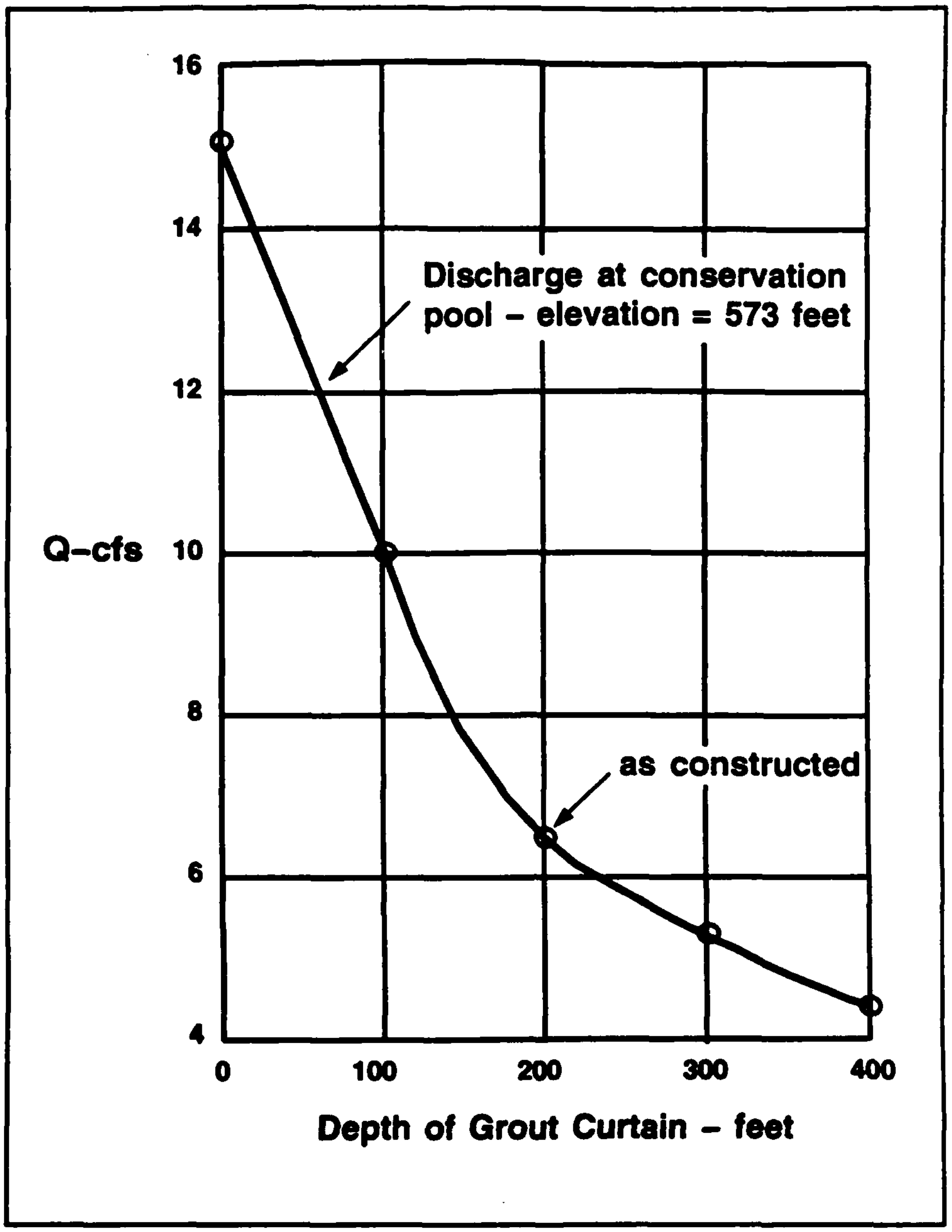

Figure 18. Effect of deepening the grout curtain

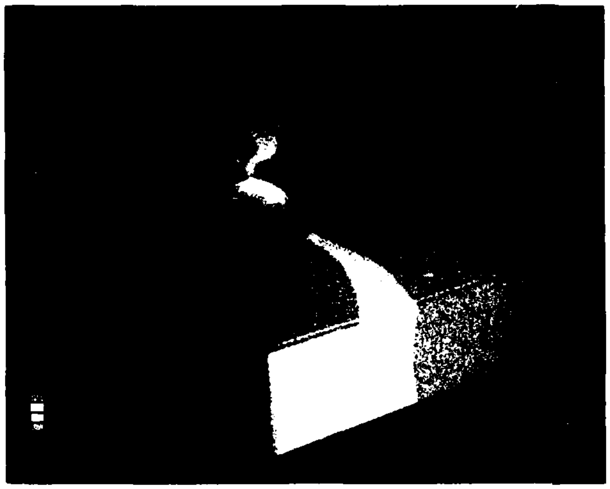

Figure 19. Piezometric heads from 3-D FE analysis - pool el = 500 ft

Figure 20. Piezometric heads across section through dam and grout curtain

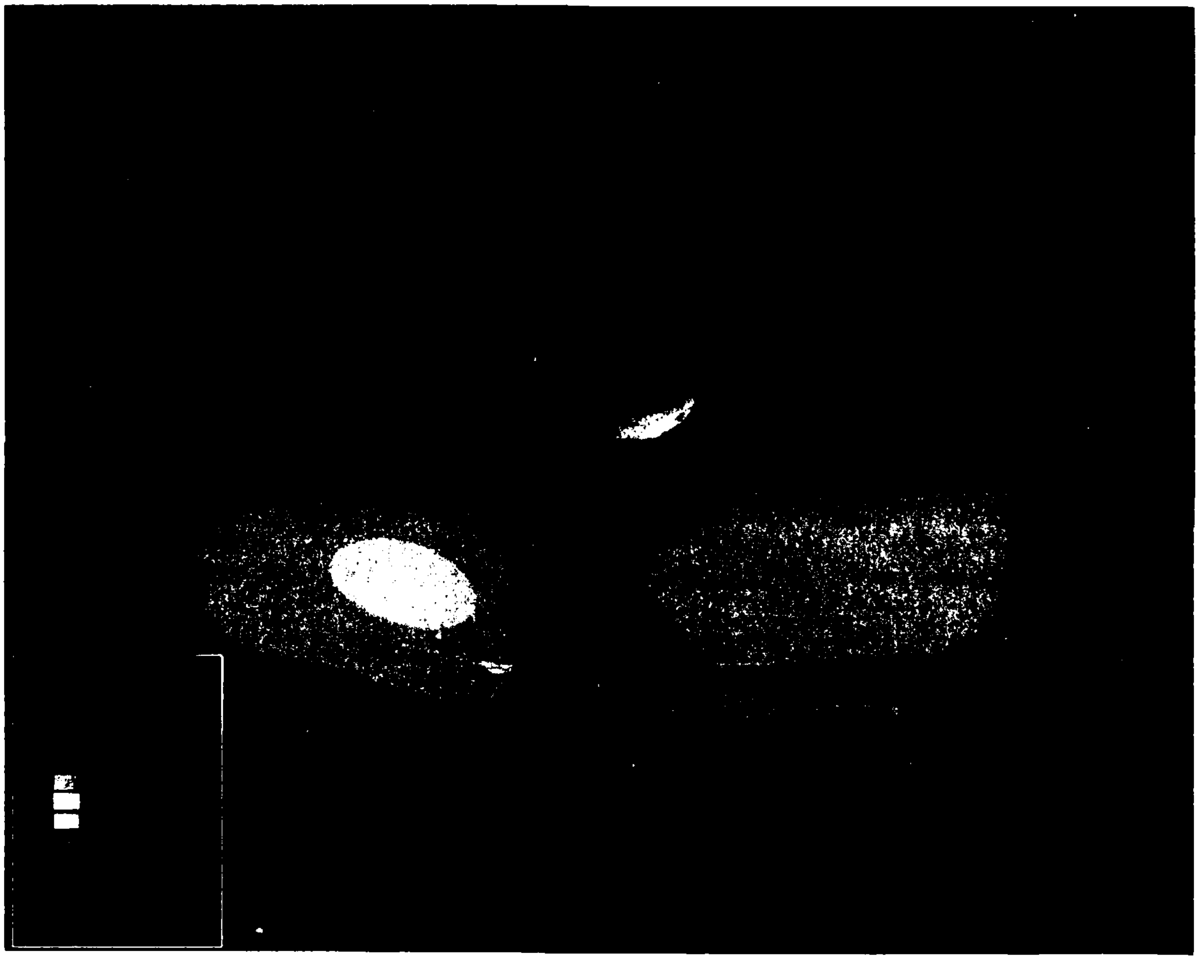

Figure 21. Flow velocities from 3-D FE analysis

Figure 22. Vertical cross section showing flow velocities in Ridge Limestone unit

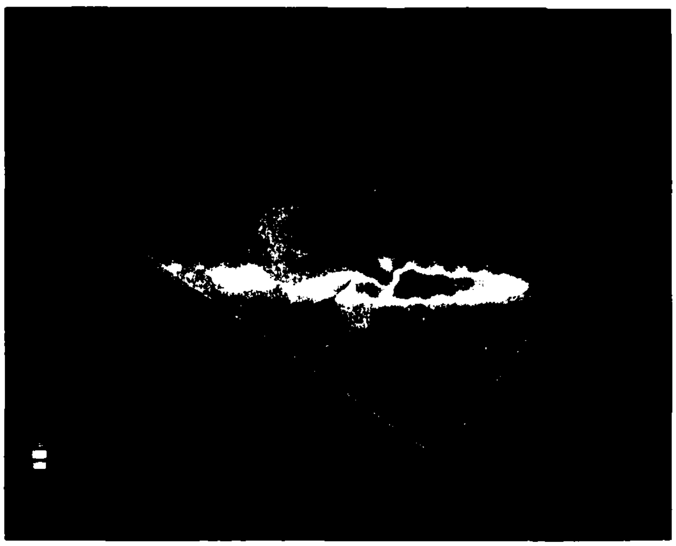

Figure 23. Horizontal section near base of dam showing flow velocities

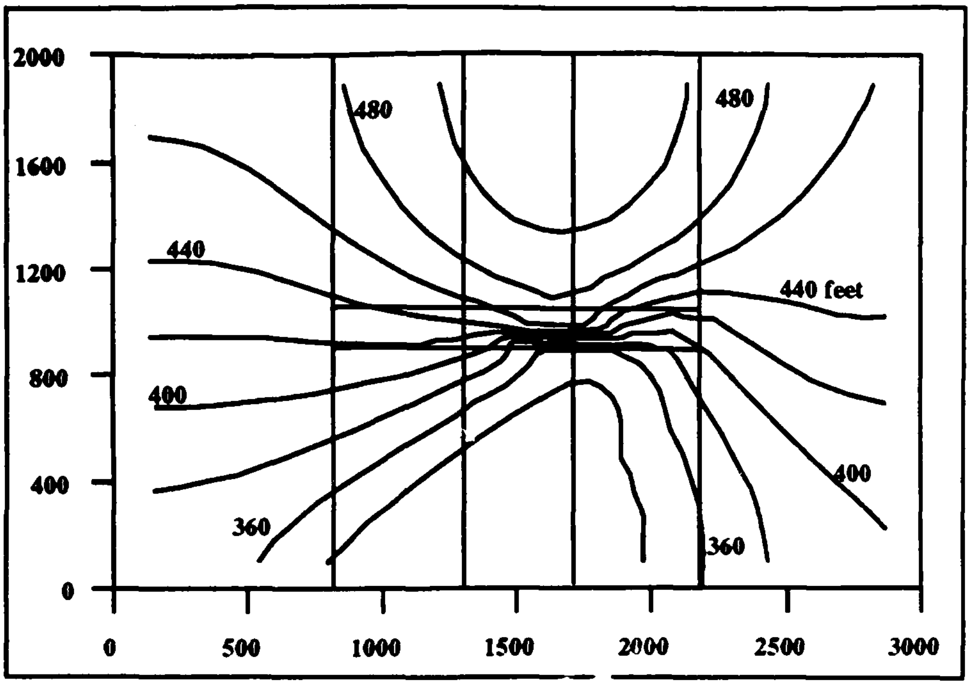

Figure 24. Contours of piezometric head at el 45 ft

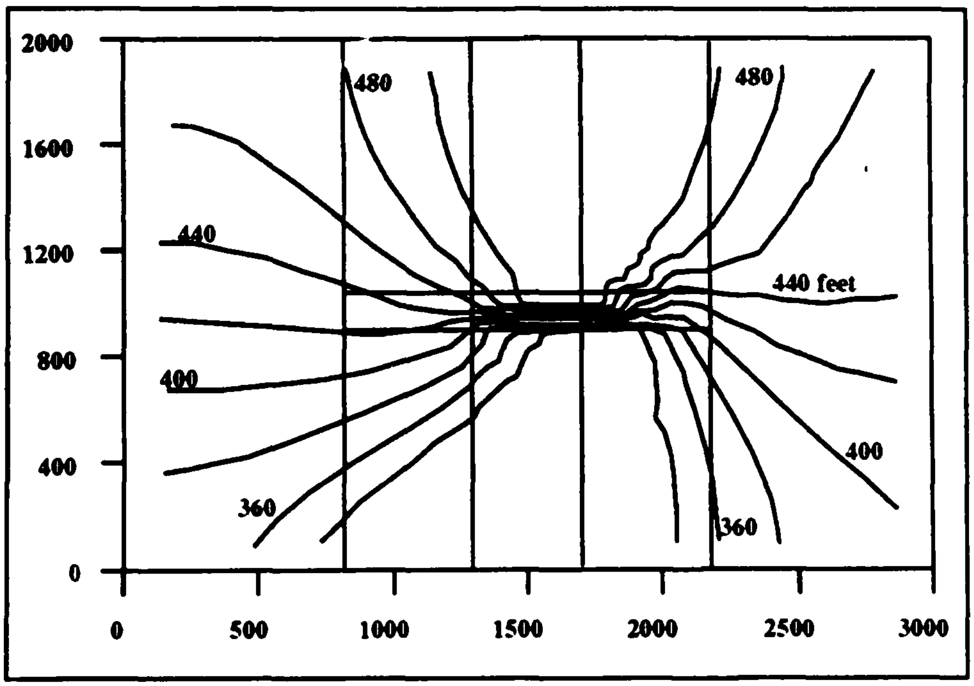

Figure 25. Contours of piezometric head at el 245 ft

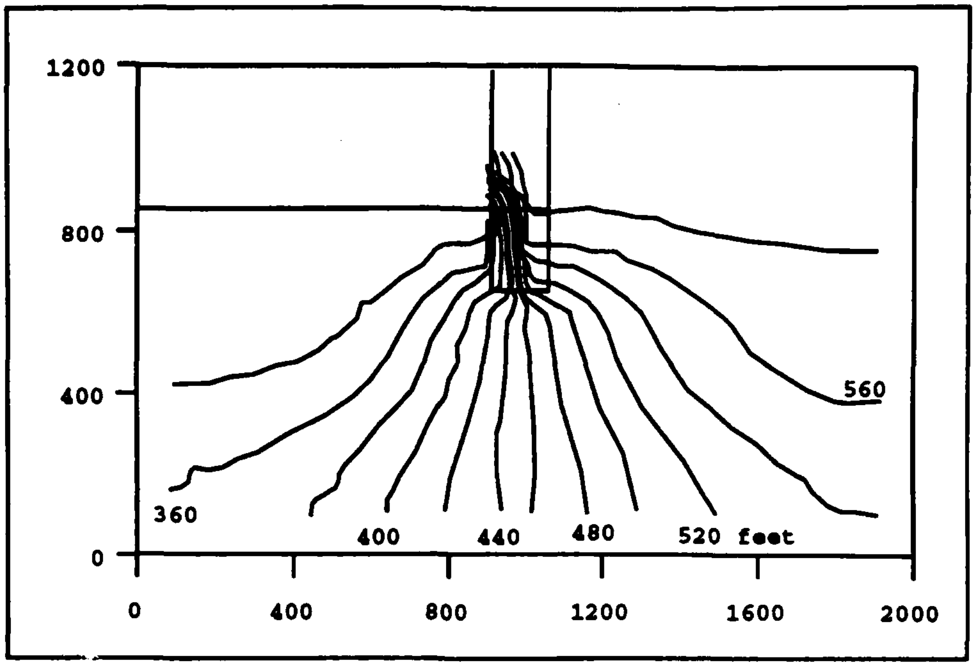

Figure 26. Contours of piezometric head along longitudinal section of valley

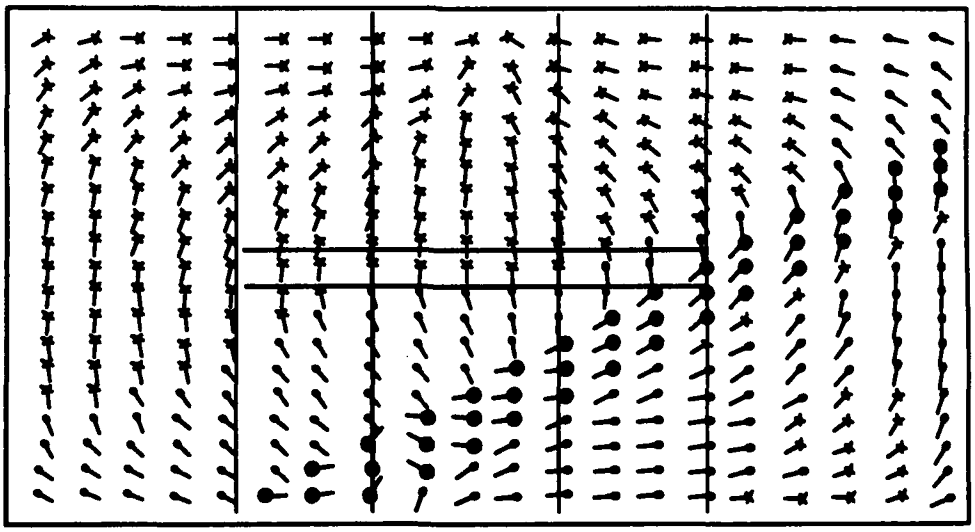

Figure 27. Direction of seepage flow on horizontal section at el-70 ft

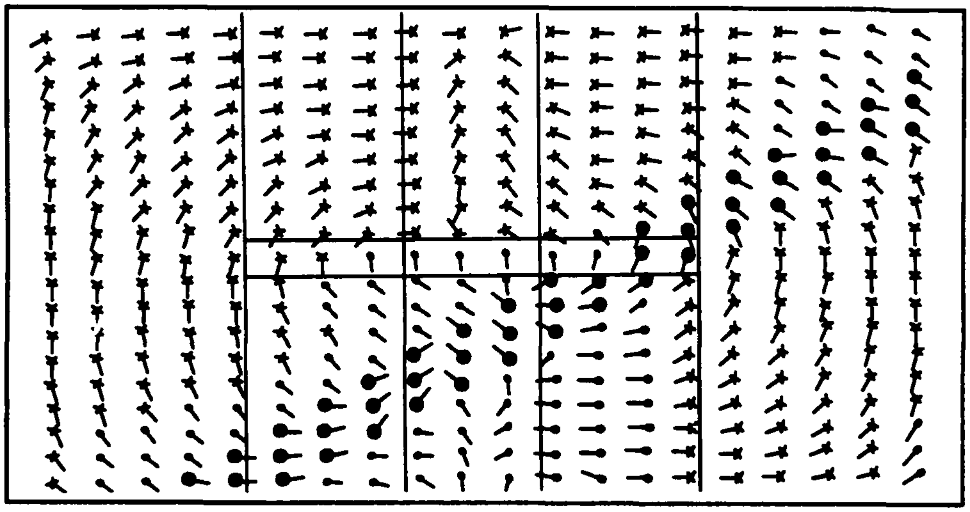

Figure 28. Direction of seepage flow on horizontal section at el 270 ft

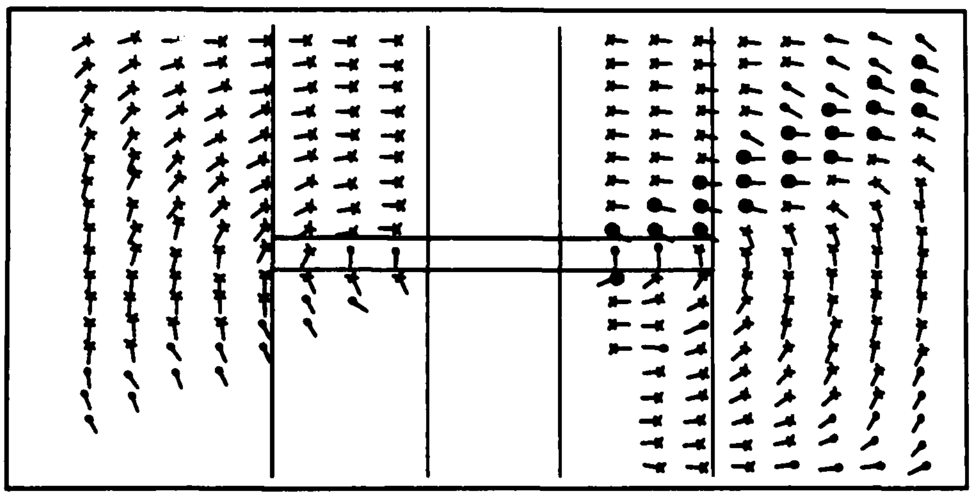

Figure 29. Direction of seepage flow on horizontal section at el 370 ft

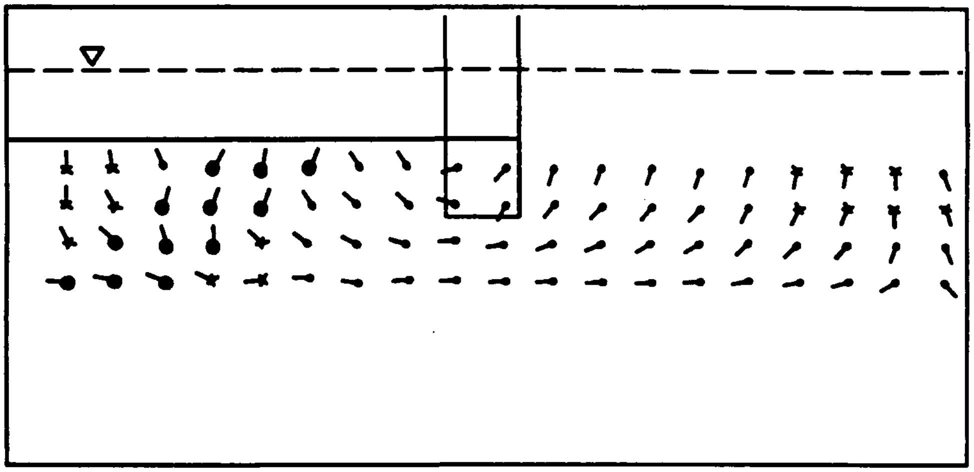

Figure 30. Direction of seepage flow on vertical section at x = 1,606 ft

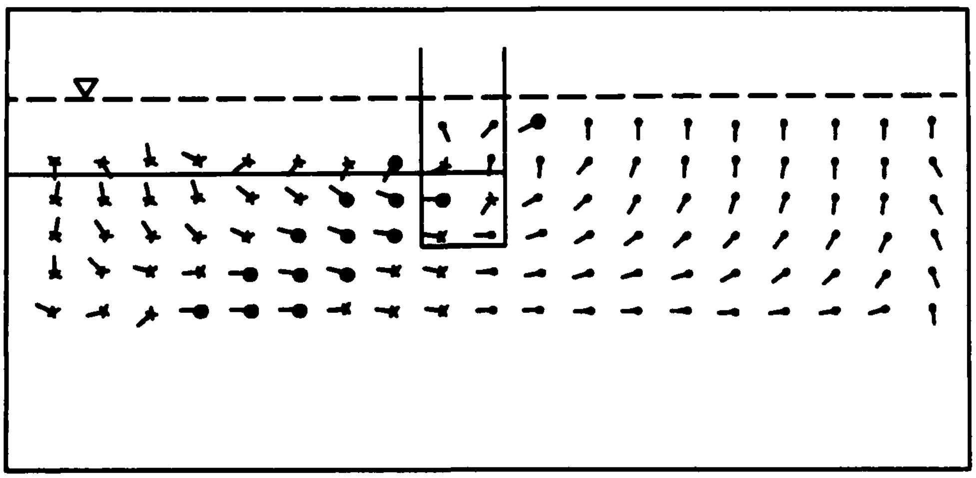

Figure 31. Direction of seepage flow on vertical section at x = 2,034 ft

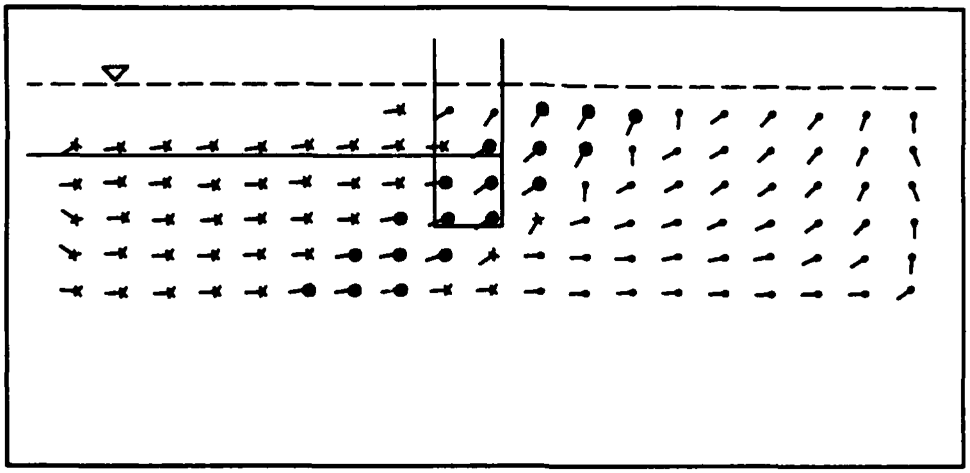

Figure 32. Direction of seepage flow on vertical section at x = 2,320 ft

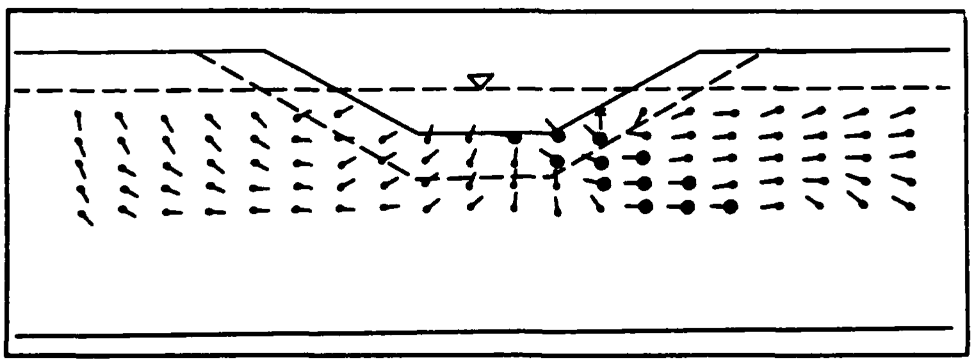

Figure 33. Direction of seepage flow on vertical section 250 ft downstream of dam core

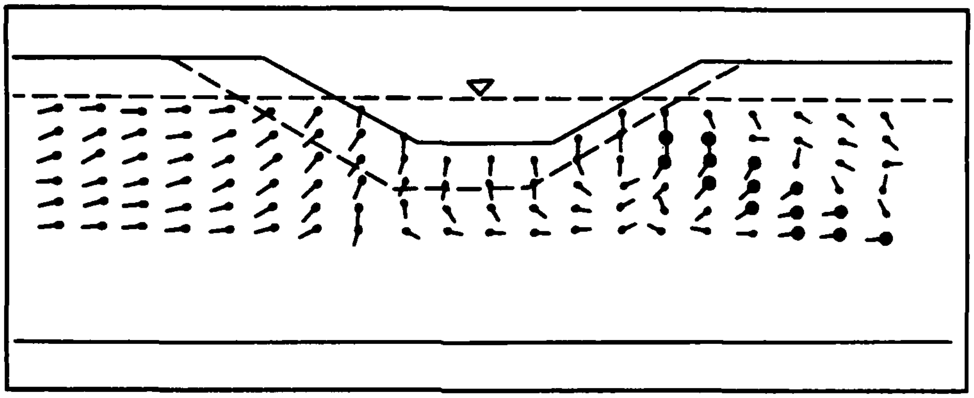

Figure 34. Direction of seepage flow in vertical section 250 ft upstream of dam core

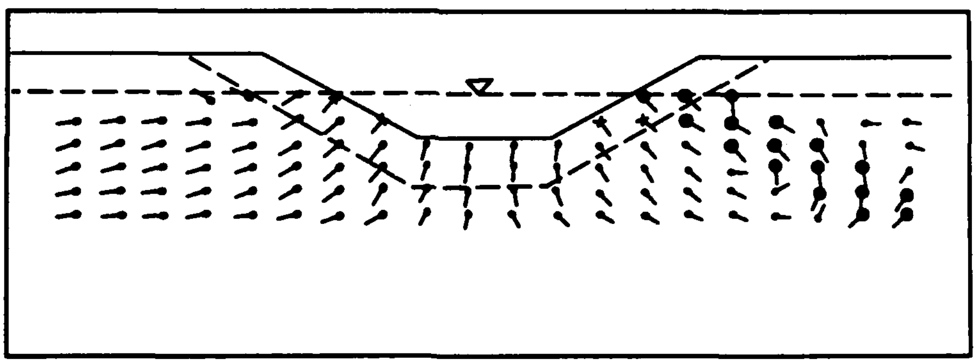

Figure 35. Direction of seepage flow in vertical section through axis of dam

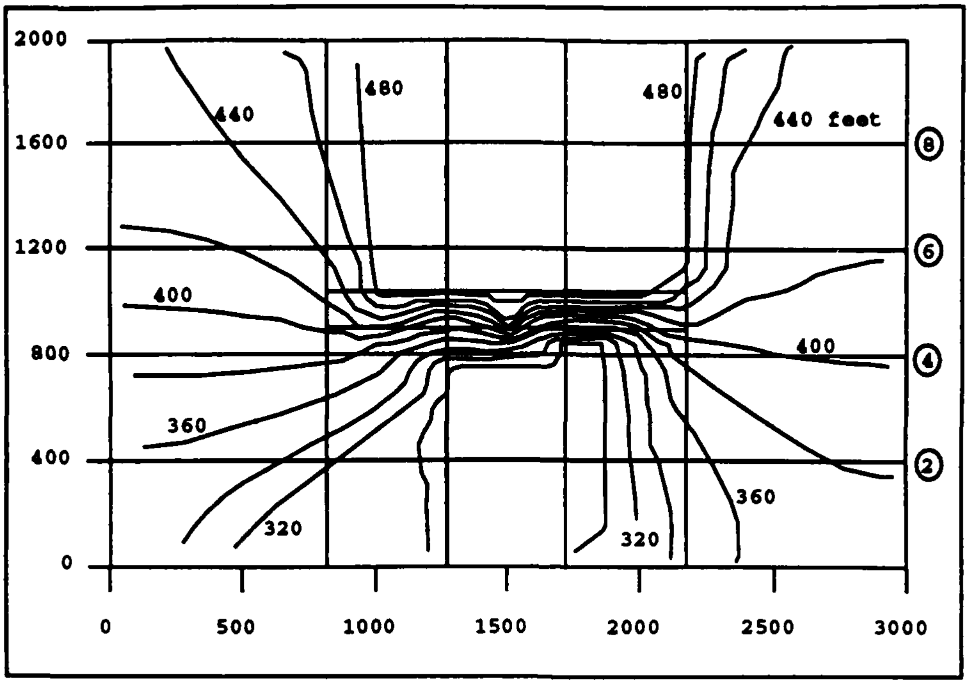

Figure 36. Contours of phreatic surface

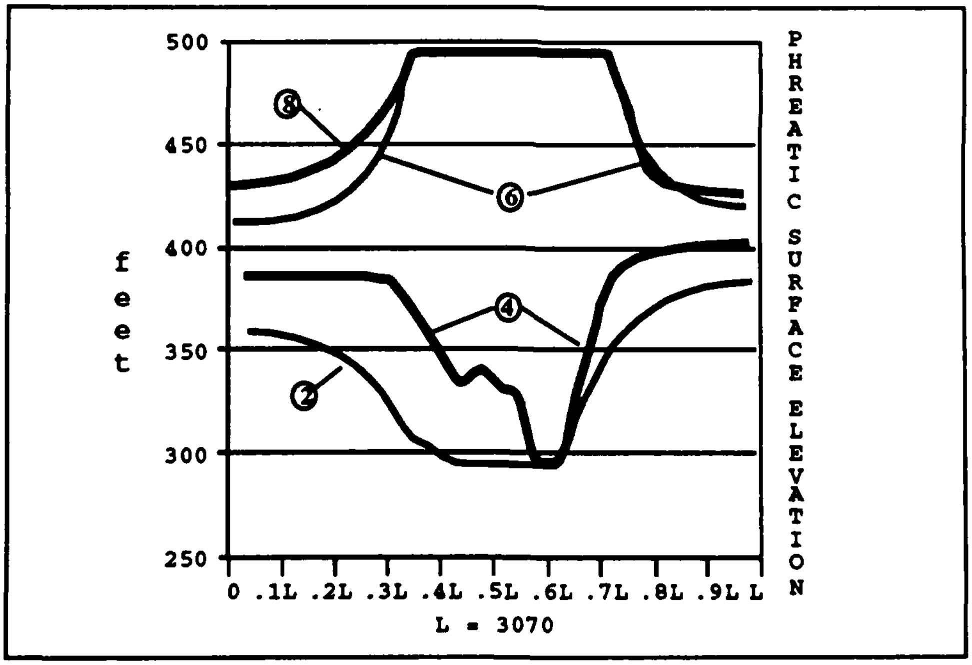

Figure 37. Selected cross valley sections through phreatic surface

Appendix A
Auxiliary Computer Programs For Cerrillos Dam Seepage Study

MESH - FE mesh generator program A2

HEADS - Program to extract piezometric heads from FE output file . . . A17

PREFLOW - Program to extract flow info from FE output file A20

FLOWS - Program to prepare flow velocity vector files A22

FLOVEC - Program to draw flow velocity vectors A25

PHREAT - Program to extract phreatic surface info FE output files A32

MESH - FE mesh generator program
January 1993

```
      PARAMETER (NPSIZE=11560,MSIZE=9150,JSIZE=500)
      INTEGER BLKNOD
      DOUBLE PRECISION XQ,YQ,ZQ,A1,A2,XC,YC,ZC
      COMMON/COOR/ X(NPSIZE),Y(NPSIZE),Z(NPSIZE),BLKNOD(MSIZE,9)
      COMMON/VOLINX/XQ(4),YQ(4),ZQ(4)
      DIMENSION IU(NPSIZE),IBC(JSIZE),JBC(JSIZE),KBC(JSIZE),PERM(12),MAT
     +TOT(12)
      CHARACTER MATDES(12)*20,CODE(5)*1,CDEP*3,EXT*4,HMAT*1
      CHARACTER JASK*1,TITLE*70,LCDES*7,OUTFIL*15,GEOL*1,C*1,SASK*1
      CHARACTER SHASK*1,SHUP*1,SHDOWN*1,ADUM*1
      DATA MATDES/'UPSTREAM SHELL      ','SHOTCRETE  CAP    . ',
     +            'IMPERVIOUS CORE     ','GROUT CURTAIN       ',
     +            'RIDGE LIMESTONE UNIT','UNITS ABOVE 800 FT  ',
     +            'UNITS BTW 750-800 FT','UNITS BTW 700-800 FT',
     +            'UNITS BTW 650-700 FT','UNITS BTW 600-750 FT',
     +            'UNITS BELOW 600 FT  ','IMPERMEABLE UNITS   '/
      EXT='.sep'
      GO TO 17
 14   PRINT*,'CODE NOT CORRECT ....TRY AGAIN'
 17   CONTINUE
      PRINT*,'ENTER PROBLEM CODE (e.g., 3LMHD100)'
      READ '(5A1,A3)',(CODE(I),I=1,5),CDEP
      IF  (CDEP.NE.'050'.AND.CDEP.NE.'100'.AND.CDEP.NE.'150'.AND.CDEP.NE
     +.'200'.
     + AND.CDEP.NE.'250'.AND.CDEP.NE.'300'.AND.CDEP.NE.'350') GO TO 14
      C=CODE(1)
      IF(C.NE.'2'.AND.C.NE.'3') GO TO 14
      IF(CODE(2).NE.'L'.AND.CODE(2).NE.'U'.AND.CODE(2).NE.'R') GO TO 14
      PRINT*,'WANT LAYERED (HORIZONTALLY) SYSTEM ? (Y/N)'
      READ '(A1)',HMAT
      IF(HMAT.EQ.'y') HMAT='Y'
      SASK='N'
      PRINT*,'WANT TO SHOTCRETE THE RIDGE UNIT ? (Y/N)'
      READ '(A1)',SHASK
      IF(SHASK.EQ.'y') SHASK='Y'
      SHUP='N'
      SHDOWN='N'
      IF(SHASK.EQ.'Y') THEN
      PRINT*,'ONLY ABOVE THE UPSTREAM SHELL ? (Y/N)'
      READ '(A1)', SHUP
      IF(SHUP.EQ.'y') SHUP='Y'
      IF(SHUP.NE.'Y') THEN
      PRINT*,'ONLY BELOW THE UPSTREAM SHELL ? (Y/N) '
      READ '(A1)',SHDOWN
      IF(SHDOWN.EQ.'y') SHDOWN='Y'
      ENDIF
      ENDIF
      IF(CODE(3).NE.'L'.AND.CODE(3).NE.'M'.AND.CODE(3).NE.'H'.
```

```
 +                  AND.CODE(3).NE.'V'.AND.CODE(3).NE.'U') GO TO 14
  IF(CODE(4).NE.'L'.AND.CODE(4).NE.'M'.AND.CODE(4).NE.'H'.
 +                  AND.CODE(4).NE.'V'.AND.CODE(4).NE.'U') GO TO 14
  IF(CODE(5).NE.'N'.AND.CODE(5).NE.'S'.AND.CODE(5).NE.'D') GO TO 14
  IF(C.EQ.'2') CODE(3)='L'
  WRITE(OUTFIL,'(5A1,A3,A4)') (CODE(I),I=1,5),CDEP,EXT
  SK=1.22E-04
  IF(CODE(2).EQ.'R') SK=1.E-04
  IF(HMAT.EQ.'Y'.AND.CODE(2).NE.'R') SK=1.4E-03
  PERM(6)=SK
  IF(CODE(3).EQ.'L') SRFL=SK
  IF(CODE(3).EQ.'M') SRFL=3.*SK
  IF(CODE(3).EQ.'H') SRFL=10.*SK
  IF(CODE(3).EQ.'V') SRFL=100.*SK
  IF(CODE(3).EQ.'U') SRFL=1000.*SK
  PERM(5)=SRFL
  IF(CODE(4).EQ.'L') SGC=.5*SK
  IF(CODE(4).EQ.'M') SGC=.2*SK
  IF(CODE(4).EQ.'H') SGC=0.1*SK
  IF(CODE(4).EQ.'V') SGC=0.01*SK
  IF(CODE(4).EQ.'U') SGC=0.000001*SK
  IF(CODE(4).EQ.'U'.AND.CODE(2).EQ.'R') SGC=0.001*SK
  PERM(4)=SGC
  PERM(1)=1000.*SK
  PERM(2)=6.4E-07
  PERM(3)=6.4E-07
  IF(HMAT.EQ.'Y') PERM(12)=1.E-12
  IF(HMAT.NE.'Y') PERM(7)=1.E-12
  IF(C.EQ.'2') THEN
  ENDIF
  IF(HMAT.EQ.'Y') THEN
  PERM(7)=7.8E-04
  PERM(8)=4.5E-04
  PERM(9)=2.6E-04
  PERM(10)=1.4E-04
  PERM(11)=1.4E-04
  IF(CODE(2).EQ.'R') THEN
  PERM(7)=PERM(6)
  PERM(8)=PERM(6)
  PERM(9)=PERM(6)
  PERM(10)=PERM(6)
  PERM(11)=PERM(6)
  ENDIF
  ENDIF
823 PRINT*,'THE FOLLOWING PERMEABILITIES ARE SET'
  PRINT*,'  '
  KD=6
  IF(HMAT.EQ.'Y') KD=12
  DO 828 I=1,KD
  PRINT 7023,I,MATDES(I),PERM(I)
828 CONTINUE
```

```
7023 FORMAT(6H    K(,I2,2H)-,A20,2H= ,1PE8.2,8H  CM/SEC)
     PRINT*,'TO CHANGE A PERMEABILITY VALUE ENTER ITS NUMBER (1-12) AND
    +'
     PRINT*,'K-VALUE (CM/SEC). ENTER 0,0 WHEN THROUGH'
     READ*,L,PK
     IF(L.EQ.0.OR.L.GT.12) GO TO 824
     PERM(L)=PK
     GO TO 823
 824 CONTINUE
     DO 591 I=1,12
 591 PERM(I)=PERM(I)/30.48
     NBORS=1
     NGRID=2
     IF(NBORS.EQ.2) NGRID=1
     DATUM=850.
     READ(CDEP,'(I3)') MELEV
     ELEV=MELEV
     PRINT*,'HEIGHT (FT) OF WATER IN POOL = ',MELEV,' FT'
     ELEV=ELEV+DATUM
     NELEV=ELEV
     NUMLAY=((NELEV+(25*NGRID+1))/(50*NGRID))*2+1
     IF(CODE(5).EQ.'N') LC=1
     IF(CODE(5).EQ.'S') LC=2
     IF(CODE(5).EQ.'D') LC=3
     IF(LC.EQ.1) PRINT*,'GROUT CURTAIN DOES NOT EXIST'
     IF(LC.EQ.2) PRINT*,'GROUT CURTAIN IS SHALLOW (100 FT DEEP)'
     IF(LC.EQ.3) PRINT*,'GROUT CURTAIN IS DEEP    (200 FT DEEP)'
     PRINT*,'OUTPUT FILE NAME IS - ',OUTFIL
     IF(C.EQ.'2') PRINT*,'THIS IS A 2-D PROBLEM'
     DO 1 I=1,NPSIZE
   1 IU(I)=0
     DO 2 I=1,MSIZE
   2 BLKNOD(I,9)=0
     NX=46/NGRID
     NY=42/NGRID
     NZ=24/NGRID
     XDEL=71.4*NGRID
     YDEL=50.*NGRID
     ZDEL=25.*NGRID
     NP=1
     DO 100 I=1,NUMLAY
     MY=NY
     YADD=0.
     IF(I-((I/2)*2).EQ.0) THEN
     YADD=25.*NGRID
     MY=NY-1
     ENDIF
     DO 200 J=1,MY
     MX=NX
     XADD=0.
     IF(I-((I/2)*2).EQ.0) THEN
```

```
      XADD=35.7*NGRID
      MX=NX-1
      ENDIF
      DO 300 K=1,MX
      Z(NP)=(I-1)*ZDEL
      Y(NP)=(J-1)*YDEL+YADD
      X(NP)=(K-1)*XDEL+XADD
      NP=NP+1
  300 CONTINUE
  200 CONTINUE
  100 CONTINUE
      NP=NP-1
      DO 588 I=NP+1,NPSIZE
  588 IU(I)=1
   50 FORMAT(2I5,4F10.2)
      NELX=NX-3
      NELY=NY-2
      NEL=1
      DO 400 K=1,NUMLAY/2
      NL=(K-1)*((NX*NY)+((NX-1)*(NY-1)))
      NU=NL+NX*NY
      DO 500 I=1,NELY
      DO 600 J=1,NELX
      BLKNOD(NEL,1)=NL+J+1+(I-1)*NX
      BLKNOD(NEL,2)=NL+J+2+(I-1)*NX
      BLKNOD(NEL,3)=NL+J+3+I*NX
      BLKNOD(NEL,4)=NL+J+2+I*NX
      BLKNOD(NEL,5)=NU+J+(I-1)*(NX-1)
      BLKNOD(NEL,6)=NU+J+1+(I-1)*(NX-1)
      BLKNOD(NEL,7)=NU+J+2+I*(NX-1)
      BLKNOD(NEL,8)=NU+J+1+I*(NX-1)
      NEL=NEL+1
  600 CONTINUE
  500 CONTINUE
      NL=NU
      NU=NL+(NX-1)*(NY-1)
      DO 550 I=1,NELY
      DO 650 J=1,NELX
      BLKNOD(NEL,1)=NL+J+(I-1)*(NX-1)
      BLKNOD(NEL,2)=NL+J+1+(I-1)*(NX-1)
      BLKNOD(NEL,3)=NL+J+2+I*(NX-1)
      BLKNOD(NEL,4)=NL+J+1+I*(NX-1)
      BLKNOD(NEL,5)=NU+J+I*NX
      BLKNOD(NEL,6)=NU+J+1+I*NX
      BLKNOD(NEL,7)=NU+J+2+(I+1)*NX
      BLKNOD(NEL,8)=NU+J+1+(I+1)*NX
      NEL=NEL+1
  650 CONTINUE
  550 CONTINUE
  400 CONTINUE
      NEL=NEL-1
```

```
    7 FORMAT(I5,3F15.1)
      PRINT*,'# NODES=',NP,'  # ELEMENTS=',NEL
C-COMPUTE BANDWIDTH OF ORIGINAL ELEMENT MESH
      MAX=0
      DO 7345 I=1,NEL
      MAX=MAX0(BLKNOD(I,7)-BLKNOD(I,1),MAX)
 7345 CONTINUE
C-DO GEOLOGY LAYERS
      GEOL='Y'
      IF(GEOL.EQ.'y'.OR.GEOL.EQ.'Y') THEN
      PRINT*,'WAIT.....ASSIGNING MATERIAL NUMBERS TO GEOLOGIC LAYERS'
      IFIND=0
      LCOUNT=0
      NCOUNT=0
      DX=-71.4*NGRID
      DY=50.*NGRID
      DZ=-50.*NGRID
      XD=3141.6
      YD=0.
      ZD=1200.
      DO 77 J=1,500
      IF(NBORS.EQ.1.AND.(J+3-(NGRID-1)).LT.22) GO TO 77
      IF(NBORS.EQ.1.AND.(J+3-(NGRID-1)).GT.24) GO TO 79
      IF(NBORS.EQ.2.AND.(J+3-(NGRID-1)).LT.44) GO TO 77
      IF(NBORS.EQ.2.AND.(J+3-(NGRID-1)).GT.49) GO TO 79
      NCOUNT=0
      DO 78 I=1,NEL
      II=I
      CALL CENTER(II,XQ(4),YQ(4),ZQ(4))
      XQ(2)=XD+(J-1)*DX
      XQ(1)=3141.6
      XQ(3)=XQ(1)
      YQ(1)=YD+(J-1)*DY
      YQ(2)=0.
      YQ(3)=YQ(2)
      ZQ(3)=ZD+(J-1)*DZ
      ZQ(1)=1200.
      ZQ(2)=ZQ(1)
      CALL VOL(A1)
      IF(J.EQ.1) A1=1.
      IF(I.EQ.0) THEN
      PRINT*,'VOL=',A1
      PRINT 99,XQ(1),XQ(2),XQ(3),YQ(1),YQ(2),YQ(3),ZQ(1),ZQ(2),ZQ(3)
      ENDIF
   99 FORMAT(4H XQ=,9F7.1)
      XQ(2)=XQ(2)+DX
      YQ(1)=YQ(1)+DY
      ZQ(3)=ZQ(3)+DZ
      CALL VOL(A2)
      IF(I.EQ.0) THEN
      PRINT*,'VOL=',A2
```

```
      PRINT 99,XQ(1),XQ(2),XQ(3),YQ(1),YQ(2),YQ(3),ZQ(1),ZQ(2),ZQ(3)
      ENDIF
      IF(A1*A2.LT.0.) THEN
      IF(IFIND.EQ.0) JJ=J
      IFIND=1
      BLKNOD(I,9)=J+3-(NGRID-1)
      NCOUNT=NCOUNT+1
      LCOUNT=LCOUNT+1
      ENDIF
   78 CONTINUE
   77 CONTINUE
   79 CONTINUE
      ENDIF
      PRINT*,'REDUCE GEOLOGIC LAYERS TO TWO MATERIALS'
      PRINT*,'MATERIAL # 5 IS THE RIDGE  LIMESTONE'
      PRINT*,'MATERIAL # 6 IS ASSIGNED TO ALL OTHER STRATA'
      DO 8834 I=1,NEL
      MMM=BLKNOD(I,9)
      BLKNOD(I,9)=6
      IF(NBORS.EQ.1.AND.MMM.GE.22.AND.MMM.LE.24) BLKNOD(I,9)=5
      IF(NBORS.EQ.2.AND.MMM.GE.44.AND.MMM.LE.49) BLKNOD(I,9)=5
 8834 CONTINUE
C-SET MATERIAL NUMBER TO 1000 IN ALL VALLEY ELEMENTS
      YQ(1)=0.
      ZQ(1)=850.
      YQ(2)=0.
      ZQ(2)=1200.
      YQ(3)=100.
      ZQ(3)=1200.
      NCOUNT=0
      LCOUNT=0
      DO 2200 I=1,NEL
      XQ(1)=1785.
      XQ(2)=2284.8
      XQ(3)=2284.8
      CALL CENTER(I,XQ(4),YQ(4),ZQ(4))
      CALL VOL(A1)
      XQ(1)=1356.6
      XQ(2)=856.8
      XQ(3)=856.8
      CALL VOL(A2)
      IF(A1*A2.LT.0.0.AND.ZQ(4).GT.850.) THEN
      BLKNOD(I,9)=1000
      IF(YQ(4).GT.900.0.AND.YQ(4).LT.1050.) THEN
      BLKNOD(I,9)=3
      LCOUNT=LCOUNT+1
      GO TO 2200
      ENDIF
      NCOUNT=NCOUNT+1
      ENDIF
 2200 CONTINUE
```

```
      MCOUNT=NCOUNT
      PRINT*,'ASSIGNED', LCOUNT,' ELEMENTS IN DAM CORE TO.........MATERI
     +AL #3'
      IF(LC.GT.1) THEN
      LCOUNT=0
      NCOUNT=0
      YQ(1)=0.
      ZQ(1)=650.
      IF(LC.EQ.2) ZQ(1)=750.
      YQ(2)=100.
      ZQ(2)=650.
      IF(LC.EQ.2) ZQ(2)=750.
      YQ(3)=0.
      ZQ(3)=1200.
      DO 66 I=1,NEL
      CALL CENTER(I,XQ(4),YQ(4),ZQ(4))
      XQ(1)=1785.
      XQ(2)=1785.
      XQ(3)=2570.4
      IF(LC.EQ.2) XQ(3)=2427.6
      CALL VOL(A1)
      XQ(1)=1356.6
      XQ(2)=1356.6
      XQ(3)=571.2
      IF(LC.EQ.2) XQ(3)=714.0
      CALL VOL(A2)
      IF(A1*A2.LT.0.0.AND.ZQ(4).GT.ZQ(1)) THEN
      IF(ABS(BLKNOD(I,9)).NE.3) THEN
      IF(YQ(4).GT.900.0.AND.YQ(4).LT.1050.) THEN
      BLKNOD(I,9)=4
      NCOUNT=NCOUNT+1
      ENDIF
      ENDIF
      ENDIF
   66 CONTINUE
      PRINT*,'ASSIGNED', NCOUNT,' ELEMENTS IN GROUT CURTAIN TO....MATERI
     +AL #4'
      ENDIF
      NCOUNT=0
      LCOUNT=0
      XQ(1)=856.8
      XQ(2)=2284.8
      XQ(3)=1356.6
      ZQ(1)=1200.
      ZQ(2)=1200.
      ZQ(3)=850.
      DO 366 I=1,NEL
      IF(BLKNOD(I,9).EQ.1000) THEN
      YQ(1)=800.
      YQ(2)=800.
      YQ(3)=500.
```

```
      CALL CENTER(I,XQ(4),YQ(4),ZQ(4))
      CALL VOL(A1)
      YQ(1)=1100.
      YQ(2)=1100.
      YQ(3)=1400.
      CALL VOL(A2)
      IF(A1*A2.LT.0.) THEN
      ENDIF
      ENDIF
  366 CONTINUE
      PRINT*,'FOUND   ',MCOUNT-NCOUNT-LCOUNT,' ELEMENTS IN VALLEY.'
      IF(C.EQ.'2') THEN
      NCOUNT=0
      DO 9234 I=1,NEL
      CALL CENTER(I,XC,YC,ZC)
      IF(XC.LT.1356.6.OR.XC.GT.1785.) THEN
      IF(HMAT.NE.'Y') BLKNOD(I,9)=7
      IF(HMAT.EQ.'Y') BLKNOD(I,9)=12
      NCOUNT=NCOUNT+1
      ENDIF
 9234 CONTINUE
      PRINT*,NCOUNT,' ELEMENTS OUTSIDE 2-D ZONE GIVEN VERY HIGH PERMEABI
     +LITY.'
      ENDIF
      IF(HMAT.EQ.'Y') THEN
      DO 9898 I=1,NEL
      C=CODE(1)
      CALL CENTER(I,XC,YC,ZC)
      IF(ZC.LT.600.AND.BLKNOD(I,9).LE.6.AND.C.EQ.'2') BLKNOD(I,9)=11
      IF(ZC.LT.600.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'3') BLKNOD(I,9)=11
      IF(ZC.LT.650.AND.ZC.GT.600.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'3') BLKN
     +OD(I,9)=10
      IF(ZC.LT.650.AND.ZC.GT.600.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'2') BLKN
     +OD(I,9)=10
      IF(ZC.LT.650.AND.ZC.GT.600.AND.BLKNOD(I,9).EQ.5.AND.C.EQ.'2') BLKN
     +OD(I,9)=10
      IF(ZC.LT.700.AND.ZC.GT.650.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'3') BLKN
     +OD(I,9)=9
      IF(ZC.LT.700.AND.ZC.GT.650.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'2') BLKN
     +OD(I,9)=9
      IF(ZC.LT.700.AND.ZC.GT.650.AND.BLKNOD(I,9).EQ.5.AND.C.EQ.'2') BLKN
     +OD(I,9)=9
      IF(ZC.LT.750.AND.ZC.GT.700.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'3') BLKN
     +OD(I,9)=8
      IF(ZC.LT.750.AND.ZC.GT.700.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'2') BLKN
     +OD(I,9)=8
      IF(ZC.LT.750.AND.ZC.GT.700.AND.BLKNOD(I,9).EQ.5.AND.C.EQ.'2') BLKN
     +OD(I,9)=8
      IF(ZC.LT.800.AND.ZC.GT.750.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'3') BLKN
     +OD(I,9)=7
```

```
      IF(ZC.LT.800.AND.ZC.GT.750.AND.BLKNOD(I,9).EQ.6.AND.C.EQ.'2') BLKN
     +OD(I,9)=7
      IF(ZC.LT.800.AND.ZC.GT.750.AND.BLKNOD(I,9).EQ.5.AND.C.EQ.'2') BLKN
     +OD(I,9)=7
      IF(ZC.LT.450.AND.CODE(2).EQ.'R') BLKNOD(I,9)=12
 9898 CONTINUE
      ENDIF
      IF(SASK.EQ.'L') THEN
      DO 6490 I=1,NEL
      CALL CENTER(I,XC,YC,ZC)
      IF(XC.GT.1570.8) BLKNOD(I,9)=12
 6490 CONTINUE
      ENDIF
      IF(SASK.EQ.'R') THEN
      DO 6491 I=1,NEL
      CALL CENTER(I,XC,YC,ZC)
      IF(XC.LT.1570.8) BLKNOD(I,9)=12
 6491 CONTINUE
      ENDIF
      IF(2.EQ.2)                    THEN
C-WRITE ORIGINAL NODE USE FILE
      DO 478 I=1,NEL
      DO 478 K=1,8
      KKK=BLKNOD(I,K)
      IU(KKK)=IU(KKK)+1
  478 CONTINUE
      OPEN(19,FILE='SCR')
      DO 479 I=1,NP
  479 WRITE(19,*) IU(I)
C-STRIP ALL VALLEY ELEMENTS AND ALL ELEMENTS ABOVE POOL
      PRINT*,'WAIT...NOW STRIPPING VALLEY ELEMENTS '
      M=1
  990 CONTINUE
      DO 770 I=M,NEL
      CALL CENTER (I,XQ(4),YQ(4),ZQ(4))
      IF(ABS(BLKNOD(I,9)).EQ.1000.) THEN
      M=I
      DO 775 J=I,NEL-1
      DO 775 K=1,9
  775 BLKNOD(J,K)=BLKNOD(J+1,K)
      NEL=NEL-1
      GO TO 990
      ENDIF
  770 CONTINUE
      PRINT*,'TOTAL NUMBER OF ELEMENTS NOW ',NEL
C-COUNT NUMBER OF ELEMENTS IN EACH TYPE OF MATERIAL
      DO 8601 I=1,12
 8601 MATTOT(I)=0
      DO 8602 I=1,NEL
      KK=BLKNOD(I,9)
      MATTOT(KK)=MATTOT(KK)+1
```

```
 8602 CONTINUE
      DO 8603 I=1,12
 8603 PRINT 8604,MATTOT(I),I
 8604 FORMAT(I10,32H ELEMENTS ASSIGNED TO MATERIAL #,I3)
      DO 375 I=1,NPSIZE
  375 IU(I)=0
      DO 88 I=1,NEL
      DO 88 K=1,8
      KKK=BLKNOD(I,K)
      IU(KKK)=1
   88 CONTINUE
      OPEN(18,FILE='NOTUSE')
      FEWIND 18
      WRITE(18,*) 'LIST OF UNUSED NODES'
      DO 89 I=1,NP
      IF(IU(I).EQ.0) WRITE(18,7) I,X(I),Y(I),Z(I)
   89 CONTINUE
      CLOSE (18)
C-STRIP UNUSED NODES FROM FILE 'SCR'
      REWIND 19
      OPEN(22,FILE='IUS')
      M=0
      DO 913 I=1,NP
      READ(19,*) JJ
      IF(IU(I).GT.0) THEN
      M=M+1
      WRITE(22,*) JJ
      ENDIF
  913 CONTINUE
      CLOSE(22)
      CLOSE(19)
C-STRIP UNUSED NODES AND RENUMBER NODES AND ELEMENTS
      PRINT*,'WAIT...REMOVING UNUSED NODES AND RENUMBERING ELEMENTS'
      NPP=NP
      IR=0
      II=0
      DO 2880 I=1,NPP
      IF(IU(I).EQ.0) THEN
      II=II+1
      DO 2882 K=I-IR,NP-1
      X(K)=X(K+1)
      Y(K)=Y(K+1)
      Z(K)=Z(K+1)
 2882 CONTINUE
      DO 2883 L=1,NEL
      IF(BLKNOD(L,7).LT.I-IR) GO TO 2883
      DO 2884 K=1,8
      IF(BLKNOD(L,K).GE.I-IR) BLKNOD(L,K)=BLKNOD(L,K)-1
 2884 CONTINUE
 2883 CONTINUE
      IR=IR+1
```

```
      NP=NP-1
      ENDIF
 2880 CONTINUE
      PRINT*,'TOTAL NUMBER OF NODES NOW ',NP
      ENDIF
      DO 444 I=1,NP
  444 IU(I)=0
      DO 188 I=1,NEL
      DO 188 K=1,8
      KKK=BLKNOD(I,K)
      IF(KKK.LT.1.OR.KKK.GT.NPSIZE) PRINT*,KKK
      IU(KKK)=1
  188 CONTINUE
      OPEN(18,FILE='NOUSE')
      REWIND 18
      WRITE(18,*) 'LIST OF UNUSED NODES'
      DO 189 I=1,NP
      IF(IU(I).EQ.0) WRITE(18,7) I,X(I),Y(I),Z(I)
  189 CONTINUE
      CLOSE(18)
C-COUNT NUMBER OF TIMES EACH NODE USED TO FORM AN ELEMENT
      DO 544 I=1,NP
  544 IU(I)=0
      DO 538 I=1,NEL
      DO 538 K=1,8
      KKK=BLKNOD(I,K)
      IU(KKK)=IU(KKK)+1
  538 CONTINUE
      PRINT*,'WAIT....LOCATING NODES TO APPLY NODAL PRESSURES'
C-FIND NODES ON UPSTREAM SIDE OF DAM TO APPLY NODAL PRESSURES
      OPEN(22,FILE='IUS')
      REWIND 22
      NUMBI=0
      NUMBJ=0
      NUMBK=0
      DO 3000 I=1,NP
      READ(22,*) IUJ
      IF(IUJ.NE.IU(I)) THEN
      IF(Y(I).GT.950.0.AND.Z(I).LE.ELEV+1.) THEN
      NUMBI=NUMBI+1
      IBC(NUMBI)=I
      ENDIF
      IF(Y(I).LT.950.0.AND.Z(I).LE.851.) THEN
      NUMBJ=NUMBJ+1
      JBC(NUMBJ)=I
      ENDIF
      IF(Y(I).LT.950.0.AND.Z(I).GT.851.) THEN
      NUMBK=NUMBK+1
      KBC(NUMBK)=I
      ENDIF
      ENDIF
```

```
 3000 CONTINUE
      CLOSE(22)
      MAX=0
      DO 7692 I=1,NEL
      MAX=MAX0(BLKNOD(I,7)-BLKNOD(I,1),MAX)
 7692 CONTINUE
      PRINT*,'WAIT.... WRITING NODE AND ELEMENT DATA TO FILE ',OUTFIL
      OPEN(15,FILE='UPNODE')
      DO 778 I=1,NUMBI
      WRITE(15,63) IBC(I),X(IBC(I)),Y(IBC(I)),Z(IBC(I)),ELEV
   63 FORMAT(I6,3F10.2,F20.1)
  778 CONTINUE
      FLEV=850.
      DO 779 I=1,NUMBJ
      WRITE(15,63) JBC(I),X(JBC(I)),Y(JBC(I)),Z(JBC(I)),FLEV
  779 CONTINUE
      DO 781 I=1,NUMBK
      WRITE(15,63) KBC(I),X(KBC(I)),Y(KBC(I)),Z(KBC(I)),Z(KBC(I))
  781 CONTINUE
      CLOSE(15)
      OPEN(14,FILE='USED')
      WRITE(14,58) (I,IU(I),I=1,NP)
   58 FORMAT(5(I8,1H(,I1,1H)))
      CLOSE(14)
      GO TO 10001
10002 CONTINUE
      DO 1800 I=1,NP
      IU(I)=0
      BDVL=0.0
      DO 1801 J=1,NUMBI
      IF(IBC(J).EQ.I) THEN
      IU(I)=1
      BDVL=ELEV-DATUM
      GO TO 1802
      ENDIF
 1801 CONTINUE
      DO 1803 K=1,NUMBJ
      IF(JBC(K).EQ.I) THEN
      IU(I)=1
      BDVL=0.
      GO TO 1802
      ENDIF
 1803 CONTINUE
      DO 1805 L=1,NUMBK
      IF(KBC(L).EQ.I) THEN
      IU(I)=2
      BDVL=Z(I)-DATUM
      GO TO 1802
      ENDIF
 1805 CONTINUE
 1802 CONTINUE
```

```
      WRITE(13,50) I,IU(I),X(I),Y(I),Z(I),BDVL
 1800 CONTINUE
C     SET MATERIAL NUMBER OF CAPPED ELEMENTS
      ICOUNT=0
      IF(SHASK.EQ.'Y') THEN
      OPEN(55,FILE='BOSSCAP')
      PRINT*,'...WAIT  FINDING SHOTCRETED ELEMENTS'
      DO 109 I=6000,NEL
      IF(BLKNOD(I,9).EQ.5) THEN
      IF(Z(BLKNOD(I,8)).LT.851.) GO TO 109
      DO 110 K=1,8
      N=BLKNOD(I,K)
      DO 110 J=1,NP
      IF(Z(J).LT.851.) GO TO 110
      IF(N.EQ.J) THEN
      IF(IU(J).EQ.1) THEN
      A1=1.
      A2=-1.
      IF(SHUP.EQ.'Y'.OR.SHDOWN.EQ.'Y') THEN
      CALL CENTER(I,XQ(4),YQ(4),ZQ(4))
      ZQ(1)=1200.
      ZQ(2)=1200.
      ZQ(3)=850.
      XQ(1)=856.8
      XQ(2)=2284.8
      XQ(3)=1356.8
      YQ(1)=1100.
      YQ(2)=1100.
      YQ(3)=1400.
      CALL VOL(A1)
      YQ(1)=3000.
      YQ(2)=3000.
      YQ(3)=3000.
      CALL VOL(A2)
      ENDIF
      IF(SHDOWN.NE.'Y'.AND.SHUP.NE.'Y') THEN
      BLKNOD(I,9)=2
      ICOUNT=ICOUNT+1
      XX=XQ(4)
      YY=YQ(4)
      ZZ=ZQ(4)
      WRITE(55,*) I,XX,YY,ZZ
      GO TO 109
      ENDIF
      IF(SHDOWN.EQ.'Y'.AND.A1*A2.GE.0.) THEN
      BLKNOD(I,9)=2
      ICOUNT=ICOUNT+1
      XX=XQ(4)
      YY=YQ(4)
      ZZ=ZQ(4)
      WRITE(55,*) I,XX,YY,ZZ
```

```
      GO TO 109
      ENDIF
      IF(SHUP.EQ.'Y'.AND.A1*A2.LT.0.) THEN
      BLKNOD(I,9)=2
      ICOUNT=ICOUNT+1
      XX=XQ(4)
      YY=YQ(4)
      ZZ=ZQ(4)
      WRITE(55,*) I,XX,YY,ZZ
      GO TO 109
      ENDIF
      ENDIF
      ENDIF
  110 CONTINUE
      ENDIF
  109 CONTINUE
      CLOSE(55)
      PRINT*,ICOUNT,' ELEMENTS ASSIGNED TO MATERIAL #2'
      ENDIF
      DO 2000 I=1,NEL
 2000 WRITE(13,55) I,(BLKNOD(I,K),K=1,9)
   55 FORMAT(10I5)
      GO TO 10003
10001 CONTINUE
      MATNO=0
      DO 378 I=1,NEL
      IF(BLKNOD(I,9).GT.MATNO) MATNO=BLKNOD(I,9)
  378 CONTINUE
      OPEN(13,FILE=OUTFIL)
      IF(LC.EQ.1) LCDES='     NO'
      IF(LC.EQ.2) LCDES='SHALLOW'
      IF(LC.EQ.3) LCDES='   DEEP'
      NOVEL=0
      WRITE(13,315) ELEV-DATUM,LCDES,OUTFIL
      WRITE(13,'(4I5,F10.2)') NP,NEL,MATNO,NOVEL,DATUM
  315 FORMAT(16H HEIGHT OF POOL=,F10.0,3X,A7,14H GROUT CURTAIN,6H FILE ,
     +A15)
      XK=1.0
      YK=1.0
      ZK=1.0
      DO 918 I=1,MATNO
  918 WRITE(13,'(I5,3E10.3)') I,PERM(I),PERM(I),PERM(I)
      GO TO 10002
10003 CONTINUE
      CLOSE(13)
C-REMOVE TEMP FILES
      OPEN(13,FILE='SCR')
      CLOSE(13,STATUS='DELETE')
      OPEN(13,FILE='NOTUSE')
      CLOSE(13,STATUS='DELETE')
      OPEN(13,FILE='IUS')
```

```
      CLOSE(13,STATUS='DELETE')
      OPEN(13,FILE='NOUSE')
      CLOSE(13,STATUS='DELETE')
      OPEN(13,FILE='UPNODE')
      CLOSE(13,STATUS='DELETE')
      OPEN(13,FILE='USED')
      CLOSE(13,STATUS='DELETE')
      STOP
      END
      SUBROUTINE CENTER(I,XC,YC,ZC)
      PARAMETER (NPSIZE=11560,MSIZE=9150,JSIZE=500)
      INTEGER BLKNOD
      DOUBLE PRECISION XC,YC,ZC
      COMMON/COOR/ X(NPSIZE),Y(NPSIZE),Z(NPSIZE),BLKNOD(MSIZE,9)
      XX=0.
      YY=0.
      ZZ=0.
      DO 100 J=1,8
      XX=XX+X(BLKNOD(I,J))
      YY=YY+Y(BLKNOD(I,J))
  100 ZZ=ZZ+Z(BLKNOD(I,J))
      XC=XX/8.
      YC=YY/8.
      ZC=ZZ/8.
      RETURN
      END
      SUBROUTINE VOL(VL)
      DOUBLE PRECISION X,Y,Z,A,B,C,D,VL,X1,X2,X3,Y1,Y2,Y3,Z1,Z2,Z3
      COMMON/VOLINX/X(4),Y(4),Z(4)
      X1=X(1)-X(4)
      X2=X(2)-X(4)
      X3=X(3)-X(4)
      Y1=Y(1)-Y(4)
      Y2=Y(2)-Y(4)
      Y3=Y(3)-Y(4)
      Z1=Z(1)-Z(4)
      Z2=Z(2)-Z(4)
      Z3=Z(3)-Z(4)
      VL=X1*(Y2*Z3-Y3*Z2)-X2*(Y1*Z3-Y3*Z1)+X3*(Y1*Z2-Y2*Z1)
      RETURN
      END
```

HEADS - Program to extract piezometric heads from FE output file

January, 1993

```
$FREEFORM
PARAMETER (NPSIZE=11560,NELSIZ=9150)
DIMENSION X(NPSIZE),Y(NPSIZE),Z(NPSIZE),IBC(NPSIZE),HEAD(NPSIZE),-
         FLOW(NPSIZE)
CHARACTER FIL*12,OUTFIL(100)*5,DUM*2,TITLE*76,B*2,O*2,A*2,ZFL*1,XFL*1,YFL*1
CHARACTER OUT(5)*1
ZFL='Z'
XFL='X'
YFL='Y'
PRINT*,'ENTER INPUT FILE NAME'
READ '(A12)',FIL
OPEN(10,FILE=FIL)
CALL REDUM(5)
READ(10,'(A76)') TITLE
CALL REDUM(5)
12 FORMAT (51X,I5)
READ(10,12) NP
CALL REDUM(1)
READ(10,12) NEL
CALL REDUM(1)
READ(10,12) MATNUM
CALL REDUM(1)
READ(10,'(51X,F11.0)') DATUM
CALL REDUM(10)
CALL REDUM(MATNUM)
CALL REDUM(10)
DO 100 I=1,NP
READ(10,*) J,IBC(I),X(I),Y(I),Z(I)
100 CONTINUE
CALL REDUM(NEL+10)
CALL REDUM(10)
DO 200 I=1,NP
READ(10,'(I6,2F13.0,1X,3A2)') J,HEAD(I),FLOW(I),B,O,A
IF(B.EQ.' *') IBC(I)=1
IF(O.EQ.' *') IBC(I)=2
IF(A.EQ.' *') IBC(I)=3
200 CONTINUE
CALL REDUM(7)
READ(10,'(40X,F12.0)') AVFLOW
" WRITE THE Z-PLANES FILES
ZMAX=-99999.
XMAX=-99999.
YMAX=-99999.
ZMIN=-ZMAX
XMIN=-XMAX
YMIN=-YMAX
DO 300 I=1,NP
IF(Z(I).GT.ZMAX) ZMAX=Z(I)
```

```
IF(X(I).GT.XMAX) XMAX=X(I)
IF(Y(I).GT.YMAX) YMAX=Y(I)
IF(Z(I).LT.ZMIN) ZMIN=Z(I)
IF(X(I).LT.XMIN) XMIN=X(I)
IF(Y(I).LT.YMIN) YMIN=Y(I)
300 CONTINUE
PRINT*,'X',XMIN,XMAX
PRINT*,'Y',YMIN,YMAX
PRINT*,'Z',ZMIN,ZMAX
J=(1.001*ZMAX/50)+1
DO 400 I=1,J
E=(I-1)*50.
IE=(E+.001)
WRITE(OUTFIL(I),'(A1,I4)') ZFL,IE
READ(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
DO 4 L=1,5
IF(OUT(L).EQ.' ') OUT(L)='0'
4 CONTINUE
WRITE(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
OPEN(12,FILE=OUTFIL(I))
DO 500 K=1,NP
IF(X(K).GT.XMIN.AND.X(K).LT.XMAX) THEN
IF(Y(K).GT.YMIN.AND.Y(K).LT.YMAX) THEN
IF(Z(K).GT.E-1.0.AND.Z(K).LT.E+1.) THEN
WRITE(12,'(I5,4E12.4,I5)') K,X(K),Y(K),HEAD(K),FLOW(K),IBC(K)
ENDIF
ENDIF
ENDIF
500 CONTINUE
CLOSE(12)
400 CONTINUE
" WRITE Y-PLANES
J=(1.001*YMAX/50)+1
DO 410 I=1,J
E=(I-1)*50.
IE=(E+0.001)
WRITE(OUTFIL(I),'(A1,I4)') YFL,IE
READ(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
DO 6 L=1,5
IF(OUT(L).EQ.' ') OUT(L)='0'
6 CONTINUE
WRITE(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
OPEN(12,FILE=OUTFIL(I))
DO 510 K=1,NP
IF(X(K).GT.XMIN.AND.X(K).LT.XMAX) THEN
IF(Z(K).GT.ZMIN.AND.Z(K).LT.ZMAX) THEN
IF(Y(K).GT.E-1.0.AND.Y(K).LT.E+1.) THEN
WRITE(12,'(I5,4E12.4,I5)') K,X(K),Z(K),HEAD(K),FLOW(K),IBC(K)
ENDIF
ENDIF
ENDIF
```

```
510 CONTINUE
CLOSE(12)
410 CONTINUE
"WRITE X-PLANES
J=(1.001*XMAX/142.8)+1
DO 420 I=1,J
E=(I-1)*142.8
IE=E+0.001
WRITE(OUTFIL(I),'(A1,I4)') XFL,IE
READ(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
DO 8 L=1,5
IF(OUT(L).EQ.' ') OUT(L)='0'
8 CONTINUE
WRITE(OUTFIL(I),'(5A1)') (OUT(L),L=1,5)
OPEN(12,FILE=OUTFIL(I))
DO 520 K=1,NP
IF(Y(K).GT.YMIN.AND.Y(K).LT.YMAX) THEN
IF(Z(K).GT.ZMIN.AND.Z(K).LT.ZMAX) THEN
IF(X(K).GT.E-1.0.AND.X(K).LT.E+1.) THEN
WRITE(12,'(I5,4E12.4,I5)') K,Y(K),Z(K),HEAD(K),FLOW(K),IBC(K)
ENDIF
ENDIF
ENDIF
520 CONTINUE
CLOSE(12)
420 CONTINUE
OPEN(12,FILE='LUCILLE')
DO 700 K=1,NP
IF(X(K).GT.XMIN.AND.X(K).LT.XMAX) THEN
IF(Y(K).GT.YMIN.AND.Y(K).LT.YMAX) THEN
IF(Z(K).GT.ZMIN.AND.Z(K).LT.ZMAX) THEN
IF(HEAD(K).GT.0.) THEN
WRITE(12,'(I5,4E15.5)') K,X(K),Y(K),Z(K),HEAD(K)
ENDIF
ENDIF
ENDIF
ENDIF
700 CONTINUE
CLOSE(10)
STOP
END

SUBROUTINE REDUM(I)
CHARACTER DUM*2
DO 100 J=1,I
READ(10,'(A2)') DUM
100 CONTINUE
RETURN
END
```

PREFLOW - Program to extract flow info from FE output file
January 1993

```
$FREEFORM
COMMON/COOR/X(11560),Y(11560),Z(11560),IBLK(9150,9)
CHARACTER FIL*12,OUTFIL(100)*5,DUM*2,TITLE*76,B*2,O*2,A*2,ZFL*1,XFL*1,YFL*1
CHARACTER OUT(5)*1,AVV*76
ZFL='Z'
XFL='X'
YFL='Y'
PRINT*,'ENTER INPUT FILE NAME'
READ '(A12)',FIL
OPEN(10,FILE=FIL)
OPEN(12,FILE='FLOWOUT')
CALL REDUM(5)
READ(10,'(A76)') TITLE
CALL REDUM(5)
12 FORMAT (51X,I5)
READ(10,12) NP
CALL REDUM(1)
READ(10,12) NEL
CALL REDUM(1)
READ(10,12) MATNUM
CALL REDUM(1)
READ(10,'(51X,F11.0)') DATUM
CALL REDUM(10)
CALL REDUM(MATNUM)
CALL REDUM(10)
DO 100 I=1,NP
READ(10,*) J,IB,X(I),Y(I),Z(I)
IF(J.NE.I) PRINT*,'ERROR --LOOP 100'
100 CONTINUE
CALL REDUM(10)
DO 110 I=1,NEL
READ(10,'(10I5)') J,(IBLK(I,K),K=1,9)
IF(J.NE.I) print*,'ERROR--LOOP 110'
110 CONTINUE
CALL REDUM(11)
DO 200 I=1,NP
READ(10,'(I6)') J
IF(J.NE.I) PRINT*,'ERR - LOOP 200'
200 CONTINUE
CALL REDUM(7)
READ(10,'(40X,F12.0)') AVFLOW
CAL  REDUM(10)
WRITE(12,'(A76)') TITLE
WRITE(12,*) AVFLOW
DO 120 I=1,NEL
READ(10,*) J,VX,VY,VZ,VR,ALPHA,BETA
IF(J.NE.I) PRINT*,'ERR -LOOP120'
CALL CENTER (J,XC,YC,ZC)
```

```
MAT=IBLK(I,9)
WRITE(12,*) I,MAT,XC,YC,ZC,VX,VY,VZ,VR,ALPHA,BETA
IF(J.EQ.0) PRINT*,'ERROR LOOP 120'
120 CONTINUE
CLOSE(10)
CLOSE(12)
STOP
END

SUBROUTINE REDUM(I)
CHARACTER DUM*2
DO 100 J=1,I
READ(10,'(A2)') DUM
100 CONTINUE
RETURN
END


SUBROUTINE CENTER(I,XC,YC,ZC)
INTEGER BLKNOD
COMMON/COOR/ X(11560),Y(11560),Z(11560),BLKNOD(9150,9)
XX=0.
YY=0.
ZZ=0.
DO 100 J=1,8
XX=XX+X(BLKNOD(I,J))
YY=YY+Y(BLKNOD(I,J))
100 ZZ=ZZ+Z(BLKNOD(I,J))
XC=XX/8.
YC=YY/8.
ZC=ZZ/8.
RETURN
END
```

FLOWS - Program to prepare flow velocity vector files

January 1993

```
$FREEFORM
PARAMETER (NPSIZE=11560,NELSIZ=9150)
DIMENSION X(NELSIZ),Y(NELSIZ),Z(NELSIZ),VX(NELSIZ),VY(NELSIZ),VZ(NELSIZ)
DIMENSION MAT(NELSIZ)
CHARACTER FIL*12,OUTFIL(100)*6,DUM*2,TITLE*76,B*2,O*2,A*2,ZFL*2,XFL*2,YFL*2
CHARACTER OUT(5)*2
ZFL='ZF'
XFL='XF'
YFL='YF'
FIL='FLOWOUT'
OPEN(10,FILE=FIL)
READ(10,'(A76)') TITLE
READ(10,*) AVFLOW
10 READ(10,*,END=11) K,MAT(K),X(K),Y(K),Z(K),VX(K),VY(K),VZ(K),V1,V2,V3
GO TO 10
11 CONTINUE
PRINT*,'# EL= ',K
NEL=K
ZMAX=-99999.
XMAX=-99999.
YMAX=-99999.
ZMIN=-ZMAX
XMIN=-XMAX
YMIN=-YMAX
DO 300 I=1,NEL
IF(Z(I).GT.ZMAX) ZMAX=Z(I)
IF(X(I).GT.XMAX) XMAX=X(I)
IF(Y(I).GT.YMAX) YMAX=Y(I)
IF(Z(I).LT.ZMIN) ZMIN=Z(I)
IF(X(I).LT.XMIN) XMIN=X(I)
IF(Y(I).LT.YMIN) YMIN=Y(I)
300 CONTINUE
PRINT*,'X',XMIN,XMAX
PRINT*,'Y',YMIN,YMAX
PRINT*,'Z',ZMIN,ZMAX
" WRITE Z-PLANES
J=(1.001*ZMAX/50)+1
DO 400 I=1,J
E=(I-1)*50.+25
IE=(E+.001)
WRITE(OUTFIL(I),'(A2,I4)') ZFL,IE
READ(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
DO 4 L=1,6
IF(OUT(L).EQ.' ') OUT(L)='0'
4 CONTINUE
WRITE(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
PRINT*,'WRITING FILE ',OUTFIL(I)
```

```
OPEN(12,FILE=OUTFIL(I))
WRITE(12,'(A76)') TITLE
WRITE(12,*) AVFLOW
DO 500 K=1,NEL
IF(Z(K).GT.E-1.0.AND.Z(K).LT.E+1.) THEN
VR=SQRT(VX(K)**2+VY(K)**2+VZ(K)**2)
WRITE(12,'(2I5,6E11.4)') K,MAT(K),X(K),Y(K),VX(K),VY(K),VZ(K),VR
ENDIF
500 CONTINUE
CLOSE(12)
400 CONTINUE
" WRITE Y-PLANES
J=(1.001*YMAX/50)+1
DO 410 I=1,J
E=(I-1)*50.+75.
IE=(E+0.001)
WRITE(OUTFIL(I),'(A2,I4)') YFL,IE
READ(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
DO 6 L=1,6
IF(OUT(L).EQ.' ') OUT(L)='0'
6 CONTINUE
WRITE(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
PRINT*,'WRITING FILE ',OUTFIL(I)
OPEN(12,FILE=OUTFIL(I))
WRITE(12,'(A76)') TITLE
WRITE(12,*) AVFLOW
DO 510 K=1,NEL
IF(Y(K).GT.E-1.0.AND.Y(K).LT.E+1.) THEN
VR=SQRT(VX(K)**2+VY(K)**2+VZ(K)**2)
WRITE(12,'(2I5,6E11.4)') K,MAT(K),X(K),Z(K),VX(K),VY(K),VZ(K),VR
ENDIF
510 CONTINUE
CLOSE(12)
410 CONTINUE
"WRITE X-PLANES
J=(1.001*XMAX/142.8)+1
DO 420 I=1,J
E=(I-1)*142.8+178.5
IE=E+0.001
WRITE(OUTFIL(I),'(A2,I4)') XFL,IE
READ(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
DO 8 L=1,6
IF(OUT(L).EQ.' ') OUT(L)='0'
8 CONTINUE
WRITE(OUTFIL(I),'(6A1)') (OUT(L),L=1,6)
PRINT*,'WRITING FILE ',OUTFIL(I)
OPEN(12,FILE=OUTFIL(I))
WRITE(12,'(A76)') TITLE
WRITE(12,*) AVFLOW
DO 520 K=1,NEL
IF(X(K).GT.E-1.0.AND.X(K).LT.E+1.) THEN
```

```
VR=SQRT(VX(K)**2+VY(K)**2+VZ(K)**2)
WRITE(12,'(2I5,6E11.4)') K,MAT(K),Y(K),Z(K),VX(K),VY(K),VZ(K),VR
ENDIF
520 CONTINUE
CLOSE(12)
420 CONTINUE
OPEN(12,FILE='FLO')
DO 700 K=1,NEL
IF(Z(K).GT.ZMIN.AND.Z(K).LT.ZMAX) THEN
VR=SQRT(VX(K)**2+VY(K)**2+VZ(K)**2)
WRITE(12,'(I5,7E11.4)') K,X(K),Y(K),Z(K),VX(K),VY(K),VZ(K),VR
ENDIF
700 CONTINUE
CLOSE(10)
STOP
END

SUBROUTINE REDUM(I)
CHARACTER DUM*2
DO 100 J=1,I
READ(10,'(A2)') DUM
100 CONTINUE
RETURN
END
```

FLOVEC - Program to draw flow velocity vectors

January 1993

```
$FREEFORM
$DEBUG
DIMENSION X(500),Y(500),V(500,3),VMAX(3),VMIN(3),VDIF(3),VV(500,3),MAT(500)
DIMENSION VEL(6),VVEL(6)
CHARACTER FIL*12,PAIR*2,BCK*1,FILNAM*13,F(13)*1,FILN*14,T(6)*19,DOS*3
CHARACTER TITLE*76
DATA BCK /'\'/
OPEN(39,FILE='SCRATCH')
5 CONTINUE
CLINE=125.
DO 16 I=1,6
VEL(I)=0.
16 VVEL(I)=0.
NUM=0
NNUM=0
FIL='
18 PRINT*,'ENTER FILE NAME OR - DOS - TO ENTER A DOS COMMAND'
READ '(A12)',FIL
IF(FIL.EQ.'D           '.OR.FIL.EQ.'DOS         ') THEN
PAUSE 'ENTER A DOS COMMAND'
PRINT*,'  '
PRINT*,'PRESS RETURN TO CONTINUE WITH PROGRAM'
CALL UPAUSE
GO TO 5
ENDIF
READ(FIL,'(12A1)') (F(I),I=1,12)
F(13)='\'
WRITE(FILNAM,'(13A1)') (F(I),I=1,13)
FILNAM=FIL//BCK
OPEN(10,FILE=FIL,STATUS='OLD',ERR=18)
READ(10,'(A76)') TITLE
READ(10,*) AVFLOW
I=1
10 READ(10,*,END=11) KK,MAT(I),X(I),Y(I),V(I,1),V(I,2),V(I,3),VR
I=I+1
GO TO 10
11 N=I-1
CLOSE(10)
DO 89 I=1,N
DO 89 J=1,3
89 VV(I,J)=V(I,J)
IF(F(1).EQ.'Z') PAIR='XY'
IF(F(1).EQ.'X') PAIR='YZ'
IF(F(1).EQ.'Y') PAIR='XZ'
PRINT*,'ENTER FACTOR FOR VECTOR LENGTHS'
READ*,FAC
PRINT*,'ENTER POOL HEIGHT'
READ*,POOL
```

```
IF(FAC.EQ.0.) FAC=0.00001
N1=2
N2=3
N3=1
IF(PAIR.EQ.'XY') THEN
N1=1
N2=2
N3=3
ENDIF
IF(PAIR.EQ.'XZ') THEN
N1=1
N2=3
N3=2
ENDIF
"FIND MAX AND MIN'S
XMAX=-9999999.
YMAX=XMAX
XMIN=-XMAX
YMIN=-YMAX
VMAX(1)=-9.E25
VMAX(2)=VMAX(1)
VMAX(3)=VMAX(1)
VMIN(1)=-VMAX(1)
VMIN(2)=-VMAX(2)
VMIN(3)=-VMAX(3)
DO 100 I=1,N
IF(X(I).GT.XMAX) XMAX=X(I)
IF(Y(I).GT.YMAX) YMAX=Y(I)
IF(X(I).LT.XMIN) XMIN=X(I)
IF(Y(I).LT.YMIN) YMIN=Y(I)
DO 100 J=1,3
IF(V(I,J).GT.VMAX(J)) VMAX(J)=V(I,J)
IF(V(I,J).LT.VMIN(J)) VMIN(J)=V(I,J)
100 CONTINUE
XDIF=XMAX-XMIN
YDIF=YMAX-YMIN
VDIF(1)=VMAX(1)-VMIN(1)
VDIF(2)=VMAX(2)-VMIN(2)
VDIF(3)=VMAX(3)-VMIN(3)
IF(YMAX.GT.XMAX) XMAX=YMAX
DIV=MAX0(ABS(VMAX(N1)),ABS(VMAX(N2)),ABS(VMIN(N1)),ABS(VMIN(N2)))
XMAX=3200.
IF(F(1).EQ.'X') XMAX=2100.
CALL PSTART(M,XMIN,XMAX,XMIN,XMAX)
DO 200 I=1,N
DO 200 J=1,3
V(I,J)=FAC*150.*V(I,J)/DIV
200 CONTINUE
"Z PLANE GRAPHICS
IF(N1.EQ.1.AND.N2.EQ.2) THEN
CALL USET('GREE')
```

```
CALL UMOVE(0.,0.)
CALL UPEN(3141.6,0.)
CALL UPEN(3141.6,2000.)
CALL UPEN(0.,2000.)
CALL UPEN(0.,0.)
CALL UMOVE(856.8,0.)
CALL UPEN(856.8,2000.)
CALL UMOVE(1356.6,0.)
CALL UPEN(1356.6,2000.)
CALL UMOVE(1785.,0.)
CALL UPEN(1785.,2000.)
CALL UMOVE(2284.8,0.)
CALL UPEN(2284.8,2000.)
CALL UMOVE(856.8,900.)
CALL UPEN(2284.8,900.)
CALL UMOVE(856.8,1050.)
CALL UPEN(2284.8,1050.)
ENDIF
"Y-PLANE GRAPHICS
IF(N1.EQ.1.AND.N2.EQ.3) THEN
CALL USET('GREE')
CALL UMOVE(0.,0.)
CALL UPEN(3141.6,0.)
CALL UPEN(3141.6,1200.)
CALL UPEN(2284.6,1200.)
CALL UPEN(1785.,850.)
CALL UPEN(1356.6,850.)
CALL UPEN(856.8,1200.)
CALL UPEN(0.,1200.)
CALL UPEN(0.,0.)
CALL USET('DASH')
CALL UMOVE(0.,POOL+850.)
CALL UPEN(3141.6,POOL+850.)
CALL UMOVE(625.,1200.)
CALL UPEN(1356.6,650.)
CALL UPEN(1785.,650.)
CALL UPEN(2517.,1200.)
CALL USET('LINE')
CALL UMOVE(1570.,POOL+850.)
CALL UPEN(1600.,POOL+900.)
CALL UPEN(1540.,POOL+900.)
CALL UPEN(1570.,POOL+850.)
ENDIF
"X-PLANE GRAPHICS
IF(N1.EQ.2.AND.N2.EQ.3) THEN
CALL USET('GREE')
CALL UMOVE(0.,0.)
CALL UPEN(2000.,0.)
CALL UPEN(2000.,1200.)
CALL UPEN(0.,1200.)
CALL UPEN(0.,0.)
```

```
CALL UMOVE(0.,850.)
CALL UPEN(500.,850.)
CALL UPEN(800.,1200.)
CALL UPEN(900.,1200.)
CALL UPEN(900.,650.)
CALL UPEN(1050.,650.)
CALL UPEN(1050.,1200.)
CALL UMOVE(900.,850.)
CALL UPEN(1050.,850.)
CALL USET('DASH')
CALL UMOVE(0.,POOL+850.)
CALL UPEN(2000.,POOL+850.)
CALL USET('LINE')
CALL UMOVE(200.,POOL+850.)
CALL UPEN(230.,POOL+900.)
CALL UPEN(170.,POOL+900.)
CALL UPEN(200.,POOL+850.)
ENDIF
DO 300 I=1,N
XI=I
IF(MAT(I).EQ.3) GO TO 300
CALL USET('BLAC')
IF(MAT(I).EQ.5) CALL USET('GREE')
IF(MAT(I).EQ.4) CALL USET('MAGE')
IF(V(I,N1)**2+V(I,N2)**2.LT.100.) THEN
IF(V(I,N1).EQ.0.AND.V(I,N2).EQ.0.) GO TO 300
AA=50.*V(I,N1)/MAX0(ABS(V(I,N1)),ABS(V(I,N2)))
BB=50.*V(I,N2)/MAX0(ABS(V(I,N1)),ABS(V(I,N2)))
V(I,N1)=AA
V(I,N2)=BB
ENDIF
TH=35./57.296
IF(F(1).EQ.'X') TH=45./57.296
CC=COS(TH)
SS=SIN(TH)
IF(MAT(I).EQ.5) THEN
IF(VV(I,N3).LT.0.) VEL(5)=VEL(5)+VV(I,N3)
IF(VV(I,N3).GT.0.) VEL(6)=VEL(6)+VV(I,N3)
IF(VV(I,N1).LT.0.) VEL(1)=VEL(1)+VV(I,N1)*SS-VV(I,N2)*CC
IF(VV(I,N2).LT.0.) VEL(3)=VEL(3)+VV(I,N2)*SS+VV(I,N1)*CC
IF(VV(I,N1).GT.0.) VEL(2)=VEL(2)+VV(I,N1)*SS-VV(I,N2)*CC
IF(VV(I,N2).GT.0.) VEL(4)=VEL(4)+VV(I,N2)*SS+VV(I,N1)*CC
NUM=NUM+1
ENDIF
IF(MAT(I).NE.5) THEN
IF(VV(I,N3).LT.0.) VVEL(5)=VVEL(5)+VV(I,N3)
IF(VV(I,N3).GT.0.) VVEL(6)=VVEL(6)+VV(I,N3)
IF(VV(I,N1).LT.0.) VVEL(1)=VVEL(1)+VV(I,N1)*SS-VV(I,N2)*CC
IF(VV(I,N2).LT.0.) VVEL(3)=VVEL(3)+VV(I,N2)*SS+VV(I,N1)*CC
IF(VV(I,N1).GT.0.) VVEL(2)=VVEL(2)+VV(I,N1)*SS-VV(I,N2)*CC
IF(VV(I,N2).GT.0.) VVEL(4)=VVEL(4)+VV(I,N2)*SS+VV(I,N1)*CC
```

```
NNUM=NNUM+1
ENDIF
CALL UMOVE(X(I)+V(I,N1),Y(I)+V(I,N2))
CALL UPEN(X(I),Y(I))
IF(V(I,N3).GE.0.AND.N3.EQ.2) CALL USET('BLUE')
IF(V(I,N3).GE.0.AND.N3.EQ.2) IC=1
IF(V(I,N3).LT.0.AND.N3.EQ.2) CALL USET('RED ')
IF(V(I,N3).LT.0.AND.N3.EQ.2) IC=0
IF(V(I,N3).GE.0.AND.N3.EQ.3) CALL USET('RED ')
IF(V(I,N3).GE.0.AND.N3.EQ.3) IC=0
IF(V(I,N3).LT.0.AND.N3.EQ.3) CALL USET('BLUE')
IF(V(I,N3).LT.0.AND.N3.EQ.3) IC=1
IF(V(I,N3).GE.0.AND.N3.EQ.1) CALL USET('RED ')
IF(V(I,N3).GE.0.AND.N3.EQ.1) IC=0
IF(V(I,N3).LT.0.AND.N3.EQ.1) CALL USET('BLUE')
IF(V(I,N3).LT.0.AND.N3.EQ.1) IC=1
IF(IC.EQ.0) THEN
CALL UCRCLE(X(I),Y(I),6.)
CALL UCRCLE(X(I),Y(I),9.)
ENDIF
IF(IC.EQ.1) THEN
CALL UMOVE(X(I)-10.,Y(I)-10.)
CALL UPEN(X(I)+10.,Y(I)+10.)
CALL UMOVE(X(I)-10.,Y(I)+10.)
CALL UPEN(X(I)+10.,Y(I)-10.)
ENDIF
300 CONTINUE
CALL UMOVE(50.,2800.)
FILN=FILNAM
FPDAY=86400.
IF(NUM.GT.0) THEN
IF(NNUM.GT.0) THEN
IF(F(1).EQ.'Z') THEN
T(1)='AV VEL (-N) HORZ  \'
T(2)='AV VEL (+N) HORZ  \'
T(3)='AV VEL (-L) VERT  \'
T(4)='AV VEL (+L) VERT  \'
T(5)='AV VEL (-Z) PERP  \'
T(6)='AV VEL (+Z) PERP  \'
ENDIF
IF(F(1).EQ.'X') THEN
T(1)='AV VEL (-N) HORZ  \'
T(2)='AV VEL (+N) HORZ  \'
T(3)='AV VEL (-L) VERT  \'
T(4)='AV VEL (+L) VERT  \'
T(5)='AV VEL (-X) PERP  \'
T(6)='AV VEL (+X) PERP  \'
ENDIF
IF(F(1).EQ.'Y') THEN
T(1)='AV VEL (-N) HORZ  \'
T(2)='AV VEL (+N) HORZ  \'
```

```
T(3)='AV VEL (-L) VERT  \'
T(4)='AV VEL (+L) VERT  \'
T(5)='AV VEL (-Y) PERP  \'
T(6)='AV VEL (+Y) PERP  \'
ENDIF
"PRINT*,'                              LIMESTONE        OTHER
XMAX=3200.
CALL UWINDO(0.,XMAX,0.,XMAX)
CALL UDAREA(1.,99.,1.,99.)
CALL UFLUSH
CALL USET('YELL')
CALL UMOVE(100.,XMAX-200.)
CALL UPRNT1(FILNAM,'TEXT')
CALL UPRNT1('        LIMESTONE        OTHER\','TEXT')
CALL UPSET('PREC',5.)
DO 87 I=1,6
CALL UFLUSH
YP=(XMAX-200.)-CLINE*(I+1)
CALL UMOVE(100.,YP)
CALL UPRNT1(T(I),'TEXT')
CALL UFLUSH
CALL UMOVE(900.,YP)
IF(I.EQ.1.OR.I.EQ.3.OR.I.EQ.5) CALL UPRNT1('-\','TEXT')
IF(I.EQ.2.OR.I.EQ.4.OR.I.EQ.6) CALL UPRNT1('+\','TEXT')
CALL UPRNT1(ABS(FPDAY*VEL(I)/NUM),'REAL')
CALL UFLUSH
CALL UMOVE(1500.,YP)
IF(I.EQ.1.OR.I.EQ.3.OR.I.EQ.5) CALL UPRNT1('-\','TEXT')
IF(I.EQ.2.OR.I.EQ.4.OR.I.EQ.6) CALL UPRNT1('+\','TEXT')
CALL UPRNT1(ABS(FPDAY*VVEL(I)/NNUM),'REAL')
CALL UMOVE(100.,100.)
CALL UFLUSH
87 CONTINUE
ENDIF
ENDIF
1222 FORMAT(1X,A19,F12.5,5X,F12.5,9H FEET/DAY)
CALL UFLUSH
CALL UPAUSE
CALL PEND
CLOSE(39,STATUS='DELETE')
IF(2.EQ.2) GO TO 5
STOP
END
SUBROUTINE PSTART(M,XMIN,XMAX,YMIN,YMAX)
COMMON/JUNK/PCT
CHARACTER DEVC*4
CHARACTER DEV*4
CHARACTER COLOR*4,CLRBCK*4
AA=XMIN
AA=YMIN
M=1
```

```
CLRBCK='WHIT'
COLOR='RED '
PCT=0.45
"    ..OUTPUT TO SCREEN OR PLOTTER...
IF(M.EQ.1) DEV='IBMH'
IF(M.EQ.2) DEV='HP4 '
CALL UDEVIC(DEV)
IF(DEV.EQ.'IBMH') CALL UDEVICE ('EGA ')
IF(DEV.EQ.'HP4 ') CALL UCOMPT(1)
CALL USTART
CALL UERASE
CALL UBACKG(CLRBCK)
CALL USET('SMALL')
IF(DEV.EQ.'IBMH') CALL USET(COLOR)
CALL USET('PERCEN')
IF(M.EQ.1) CALL UDAREA(1.,99.,1.,99.)
IF(M.EQ.2) CALL UDAREA(1.,75.*PCT,10.,75*PCT)
CALL UWINDO(0.,1.0*XMAX,0.,1.0*YMAX)
CALL UOUTLN
"CALL USET('SOFTWARE')
CALL USET('HARD')
PSFT=1.
IF(M.EQ.2) PSFT=.5
CALL UPSET('VERT',100.)
CALL UPSET('HORI',100.)
IF(M.EQ.2) CALL USET('SOFT')
RETURN
END
SUBROUTINE PEND
CALL UFLUSH
CALL UEND
RETURN
END
```

PHREAT - Program to extract phreatic surface info from FE file
January 1993

```
$FREEFORM
$DEBUG
COMMON/COOR/X(11560),Y(11560),Z(11560),XX(1000),YY(1000),ZZ(1000)
CHARACTER FIL*12,OUTFIL(100)*5,DUM*2,TITLE*76,B*2,O*2,A*2,ZFL*1,XFL*1,YFL*1
CHARACTER OUT(5)*1,AVV*76
ZFL='Z'
XFL='X'
YFL='Y'
PRINT*,'ENTER INPUT FILE NAME'
READ '(A12)',FIL
OPEN(10,FILE=FIL)
OPEN(12,FILE='PHREOUT')
CALL REDUM(5)
READ(10,'(A76)') TITLE
CALL REDUM(5)
12 FORMAT (51X,I5)
READ(10,12) NP
CALL REDUM(1)
READ(10,12) NEL
CALL REDUM(1)
READ(10,12) MATNUM
CALL REDUM(1)
READ(10,'(51X,F11.0)') DATUM
CALL REDUM(10)
CALL REDUM(MATNUM)
CALL REDUM(10)
DO 100 I=1,NP
READ(10,*) J,IB,X(I),Y(I),Z(I)
IF(J.NE.I) PRINT*,'ERROR --LOOP 100'
100 CONTINUE
CALL REDUM(10+NEL)
CALL REDUM(11)
DO 200 I=1,NP
READ(10,'(I6,F13.0,F13.0,A3,A2,A2,3F13.0)') J,H,H,B,O,A,X(I),Y(I),Z(I)
IF(J.NE.I) PRINT*,'ERR - LOOP 200'
200 CONTINUE
J=1
DO 55 I=1,NP
IF(Z(I).NE.0.) THEN
XX(J)=X(I)
YY(J)=Y(I)
ZZ(J)=Z(I)
J=J+1
ENDIF
55 CONTINUE
DO 77 I=1,J-1
77 WRITE(12,*) I,XX(I),YY(I),ZZ(I)-555.0
CLOSE(10)
```

```
CLOSE(12)
STOP
END

SUBROUTINE REDUM(I)
CHARACTER DUM*2
DO 100 J=1,I
READ(10,'(A2)') DUM
100 CONTINUE
RETURN
END
```

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Foundation seepage in excess of design estimates occurred following the first filling of the new Cerrillos Dam located in Puerto Rico. This 323-ft high earth-rockfill dam, constructed by the U.S. Army Corps of Engineers, is situated on a foundation of steeply dipping limestones, siltstones, and tuffs. Seepage is controlled by an impermeable clay core located within the dam and by a two-line grout curtain which extends 20 ft into the foundation rock. A drainage collection system located within the downstream toe of the rockfill shell collects and monitors the seepage discharge. Since measured seepage discharges were approximately six times greater than the design estimate, a review of the seepage regime was undertaken.

The original design seepage estimate was made using hand-drawn flow net procedures for an idealized two-dimensional (2-D) vertical section taken through the dam. A design seepage estimate of 1.0 cu ft per second (cfs) was obtained. This 2-D analyses failed to satisfactorily account for the cross-valley components of seepage under the grout curtain through more permeable limestone formations present in the dam's left abutment. A three-dimensional (3-D) finite element (FE) method seepage analysis was conducted and yielded excellent

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agreement with the measured seepage discharges at different pool elevations. This 3-D analysis provided a means to include the effects of the complicated geologic conditions which exist at the site. At present, a seepage discharge of 6.5 cfs at the conservation pool elevation is predicted. This report describes the essential features of the 3-D FE code and demonstrates the use of 3-D visualization techniques to exhibit the structural members of the dam, the complicated geologic foundation conditions, and the voluminous output of the FE analyses. An important finding of the study was that the geologic interpretations and the permeability properties which were available during the design could be used with very little modification to provide excellent agreement with the measured rates of seepage. This report also describes the simulation of different remediation schemes (e.g., shotcreting the valley walls and deepening the grout curtain) to reduce seepage.